A PROPOSED METHOD OF
IDENTIFYING AND TRACKING TORNADOES

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By

CARL WILLIAM MILLER

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APPROVED BY:

Herbert L. Jones
Chairman, Thesis Committee

Chas. F. Cameron
Member of the Thesis Committee

A. Naeter
Head of the Department

D. C. McIntosh
Dean of the Graduate School

PREFACE

Charles D. Warner's old saying that "Everybody talks about the weather but nobody does anything about it" is still essentially true. But if we cannot modify the weather to suit our purpose, the next best thing is to try to predict it with the greatest accuracy possible so as to be prepared for it. Only one account need be read of a destructive tornado to justify careful research and study on the prediction of this type of storm.

The purpose of this thesis is to describe in detail the work that has been done by the author toward a solution of the problem of identifying and tracking these tornadoes. The study was undertaken in order to lay the foundation for a system designed to accomplish this identification and tracking while the tornado is still in the process of formation.

The first part of the thesis is devoted to basic considerations of the problems involved in a complete tracking system and their proposed solutions. The second part concerns the specific problem of identification.

This work was undertaken with the expectation that upon completion of the project, it will be possible to institute a warning system similar to that now employed in the south and east portions of the United States for hurricanes.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Doctor H. L. Jones for his many helpful suggestions and assistance in preparation of this material. Thanks are also due to Doctor C. A. Dunn and Professor J. R. Norton for their interest in the problem and aid in securing necessary equipment, and to Mr. J. A. Woods of the Engineering Experiment Station shop for his excellent co-operation in modifying photographic equipment.

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CHAPTER I

The tornado is one of the most treacherous and destructive storms known, and unlike many other types of storms, it has been virtually unpredicatable. It usually strikes at night when people are unprepared, and forms so suddenly that it gives practically no warning.

PRELIMINARY INVESTIGATIONS

At a meeting on September 25, 1947, with Doctor C. A. Dunn of the Oklahoma A. & M. Engineering Experiment Station and Doctor H. L. Jones of the Electrical Engineering Department at Oklahoma A. & M. College, the possibility of tracking these tornadoes and giving advance warnings to towns and cities in their paths was discussed. Several possible methods of tracking were considered. The two selected as being the most likely possibilities were by radar and, if the tornado cloud contained lightning, by direction finding equipment. At the time direction finding seemed the more logical choice. Such a system would operate on the principle of being direction sensitive to the static emanating from the storm, and would require two or more stations to effect a triangulation scheme. An investigation was then undertaken by the author concerning the problem as a whole, particularly on the nature of tornadoes and their characteristics. Included in this study was an examination of various direction finding systems with particular emphasis on work by the engineers at the University of Florida in their hurricane tracking project.[1]

However, the most difficult aspect of the problem appeared to be the actual discovery and identification of the tornadoes. Obviously warnings could not be issued to towns each time an ordinary storm containing lightning was approaching. This aspect of the problem was postponed until more could be learned concerning the nature of the tornado, and some preliminary work could be done on the design of the tracking system.

Humphreys describes briefly the general features of the tornado and in his treatment remarks, "Nearly, or quite invariably lightning accompanies the tornado, but seldom, if at all, occurs in the funnel cloud."[2] Consequently, it appeared that it would be possible to effect tracking with direction finding equipment. Personal observations, together with those of other residents of this locality, are that although lightning may not occur in the funnel, it certainly occurs very close to it.

Conversion was begun of some war surplus BC-433G Aircraft Direction Finding Receivers for this work, with the idea of using two receivers with fixed crossed loop antennas. This method of reception has been in use for some time. By placing the loops at right angles, and coupling the output of one receiver to the horizontal plates, and the other to the vertical plates of an oscilloscope, the direction of an incoming signal appears instan-

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[1] J. Weils and W. Mason, University of Florida Bulletin No. 3, October, 1946.

[2] W. J. Humphreys, Physics of the Air, pp. 218-219.

taneously. This direction is found by noting the orientation of the closed loop on the face of the oscilloscope with respect to a scale marked to 180 degrees. This assumes, of course, that the complete circuits of both receivers, including loops, have identical gain and phase shift. Thus the receivers to be converted would have to be completely compensated in this respect. Also it is worth noting that there could exist 180 degree ambiguity with such a system. This difficulty could be eliminated by using two or more stations and employing the triangulation method mentioned previously for locating the storm center.

It is, of course, possible to use a sense antenna to eliminate the 180 degree ambiguity. Considerable work was done along this line in which the theory was advanced that the mean energy radiated was constant from all lightning discharges.[3] One worker in this field plotted a map of distance vs. received intensity for the whole continent of Australia, and after corrections were made for terrain irregularities attained some successes in spotting storms from a single station. However, in our case the triangulation method was considered to be the only practical one.

An examination of the literature covering the work which had been done by the University of Florida and the "Sferics" group of the U. S. Army on their hurricane tracking work dis-

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[3] "Discussion on Thunderstorm Researches." Quarterly Journal of Meteorological Society. Volume 62, p. 499, 1936.

closed that they have generally used frequencies of 7 to 10 kilocycles--this being the band of frequencies found to contain most of the energy from lightning discharges.[4] This is explained by them to be due to the fact that the quasi-period of such discharges is from 100 to 250 micro-seconds. It is interesting to note that this figure does not agree too well with that proposed by Appleton, Watt and Herd, who made extensive tabulations, and found most of these durations to be greater than 1000 micro-seconds.[5] It is possible that Watt, Appleton and Herd considered total time, and the other group measured only the interval of high energy concentration.

The BC-433G Receivers had a frequency range extending downward only to 200 kilocycles. However, it was felt that this might be of considerable advantage in our case, since we were desirous of limiting our range of reception to the tornado area. The "Sferics" group, on the other hand, tried to receive signals from as far away as possible.[6]

Furthermore it has been observed that the loop method of direction finding is susceptible to night errors--these errors being worse at lower frequencies. Such error is found on all

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[4] "Static d-f Reveals Storm Location." Electronics. April, 1946, p. 212.

[5] E. V. Appleton, R. A. Watson Watt and J. F. Herd, "On the Nature of Atmospherics -- II," Proceedings of the Royal Society of London. Ser. A. Vol. III, pp. 615-76.

[6] J. Weils and W. Mason, Loc. Cit.

loop systems, and is due to the horizontal component of reception which occurs when high angle radiation is experienced.

ORGANIZATION OF PROJECT

At this time another meeting was held concerning the total project. In the light of what had been learned, a more specific program was outlined. The need was still strongly felt for a system of discovering or identifying the tornadoes by means of some sort at the "base" or tracking stations. By this time, another graduate student, Mr. Bruce Blackman, had become interested in the project and agreed to take over the problem of building phase shift equalizers and other circuits pertinent to the tracking system. This left more time for the author to devote to the identification problem, outside of advice to Mr. Blackman, when necessary, and the planning of the project as a whole.

At the same meeting another problem was discussed, which seemed to demand attention. This was the previously mentioned "night effect" error. Two factors would be in our favor in this respect. Operation at a higher frequency would lessen the error of angle considerably and, since our receiving stations would be closer to the storm source, the distance error would be less for a given angle. However, under extreme conditions the calculated storm location could still be in error by a matter of miles, and thus it would be desirable to eliminate such discrepancies, if possible.

The possibility of using the Adcock antenna was suggested. This is a type which was especially designed for eliminating night error. Consequently, the Adcock antenna was investigated in detail and compared with other directional antennas. The disadvantage of such an antenna would in our case be fundamentally a lack of sensitivity, being at most the equivalent of a one turn loop. Therefore, such an antenna of convenient physical size would have dimensions very small compared with our wavelength, whereas a loop could consist of many turns. The idea was not discarded, however, since the Adcock compares favorably with the loop insofar as signal-to-noise ratio is concerned. Conceivably, it could still be used, but would require a receiver with much higher total gain than that later employed.

The Federal Communications Commission was contacted, since they were known to have made many recent developments on Adcock and other directional antennas. As a result of our correspondence, we were fortunate enough to arrange a visit to their station in Broken Arrow, Oklahoma, the same day Commissioner J. J. Sterling and other members from Washington, D. C., were there on an inspection tour. While there, we gained a great deal of information about the Adcock type of antenna and other types of directional antennas.

Another graduate student, Mr. Joseph Oursler, made the trip with us, as he was interested in antenna research. After the trip, he agreed to carry on with the night error problem.

Subsequent discussion of the various possibilities resulted in the selection of the loop antenna as being the most desirable type of antenna, provided that the attendant error could be eliminated. Research was therefore begun with this objective as a goal.

CHAPTER II

CHOICE OF TORNADO IDENTIFICATION METHOD

It appeared advisable to further explore the library for all subjects relating to tornadoes and atmospherics for a clue as to some peculiar identifying characteristic. The formation period of a tornado is very short, and consequently a rapid identification method was considered essential. Several ideas were gained which will be enumerated and discussed in the following paragraphs.

One of the references quoted observers of a tornado as being able to hear with no acoustical aid a quite distinct roar at a distance of five miles.[1] This suggested the possibility of using something like one of the very sensitive aural detectors employed for the detection of enemy aircraft. Further investigation of this possibility indicated that it would be cumbersome and unlikely of success, although not altogether impractical.

Another approach was based on observation of the steady "hiss" of static accompanying whirlwinds, which the author noted at White Sands, New Mexico, while engaged on another problem. The disturbance was definitely due to the whirlwind. This phenomenon was evident while readings were taken on a receiver so far away that its antenna was definitely clear of disturbed air laden with sand particles. At that time the

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[1] "The 13 Tornadoes of March 28, 1928." Monthly Weather Review, April, 1920.

observations were further checked with insulated antennas to completely eliminate the possibility that sand particle collisions with the antenna were causing the disturbance. In a dust particle experiment, it was demonstrated that very high potentials could be caused by disturbing small amounts of powder with a puff of air.[2] In particular the statement is made, "It is thus easy to understand how the very high potential gradient--over 10,000 volts per metre--may arise during a dust storm, and the lightning flashes which are stated to accompany eruptions of fine ashes from volcanoes may perhaps be referred to the same cause."

On the basis of the above evidence, serious consideration was given to a method for searching for the steady hiss caused by sand particle collisions of tornadoes. Winds in a tornado funnel reach enormous proportions--100 to 500 miles per hr., and there is always considerable sand and debris present, especially during contact of the funnel with the earth.

However, observations made during actual thunderstorms indicated that the mean level of static due to very frequent lightning discharges might be of such a high level as to mask any such effect.

The approach which seemed to give greatest promise, and the one which was finally used, was based on theoretical considera-

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[2] W. A. D. Rudge, "On the Electrification Produced During the Raising of a Cloud of Dust." Proceedings of the Royal Society of London. Ser. A, Vol. 90 (Feb., 1914) pp. 256-63.

tions of the nature of lightning and tornadoes. These considerations will be presented to form a background for the proposed method of identification. Then will follow a summary of a reference which contained certain conclusions favoring the theory of the proposed tornado identification method, and which also served somewhat as a guide in experimental work.

It is hardly necessary to point out to anyone acquainted with the tremendous destructive power of tornadoes that in some manner a vast amount of potential energy is stored in the storm area. This energy is released during the period of cyclonic activity in the form of kinetic energy embodied in violent air motion. The energy must, of course, be gained from the solar system. This energy is usually accumulated on a moist, still day during which time the molecules of air and water vapor receive a great amount of thermal energy. The otherwise normal rise of this mass of warm air through the cooler upper atmosphere is prevented by certain opposing forces. An effective boundary layer is formed wherein the warm moist air is, so to speak, "pushing" upward against the cool dry air along a smooth, unbroken surface. If, however, for some reason a "cold front" extending the total height of both the warm and cold layers begins moving in, the warm air rushes upward causing a vortex or "swirl" along the moving face of the cold front. A classic demonstration of this occurrence is provided in a laboratory experiment. A beaker is half filled with oil and then water is very carefully poured over the oil. The water remains on top as long as the barrier surface between is undisturbed. When this barrier is broken, however, the oil swirls upward forming a vortex similar to that of the tornado.

Such unusual conditions surrounding the occurrence of a tornado strongly indicated the probability that the accompanying lightning discharge would be of quite different form from that of the ordinary storm. The two strata of air formed in a manner similar to that of the oil-water experiment are necessarily of different composition and consequently should have different dielectric constants and voltage breakdown characteristics. Thus, when a cloud above them accumulates a charge with respect to ground, a different potential gradient should exist in each medium. It would appear logical then, that actual ionization and discharge breakdown would consist of two successive operations, one following the other very closely in time.

Also, since wind velocities in and around the tornado reach 100 to 500 miles per hour, it would seem that any discharge, once formed, would be "blown out" very rapidly in much the same manner as the air blast "blowout" type of switch used commercially to prevent sustained arcs upon the opening of such a switch. This should discourage several types of discharge common to the ordinary thunderstorm. One such type is simply a long-persistence discharge due to a heavy initial cloud charge. Once a path has been ionized a steady discharge occurs until sufficient charge has been transferred. Another commonly occurring type is that of a series of discharges across the same ionized path following in very rapid succession. Such a type is commonly known as oscillatory.

As contrasted against the above two types, a discharge occurring in a region of violent winds should be a single, sharp discharge of comparatively short duration.

The most convenient means of portraying the nature of a lightning stroke is by observing the induced potential variation on an antenna placed above the earth. In a study of these potential variations or "atmospherics" as they are commonly called, an antenna may be thought of as simply a capacitance with respect to ground. Observation of potential variation across the terminals of such a capacitance immediately presents a problem. Any practical measuring circuit that has yet been devised has a finite value of resistance across its input terminals. When connected to the terminals of an otherwise pure capacitance, the circuit is altered so as to possess a definite time constant. If the resistance between capacitance terminals, e.g. antenna and ground, is made high enough to produce a large RC time constant compared to the duration of atmospherics, the capacitance will still be allowed to follow potential variations with negligible deviation. If, on the other hand, the RC time constant is made short compared to duration of the atmospherics, and potential variation is measured across the resistance connected to the capacitance terminals, a measurement of $\frac{dE}{dt}$ will result where E is the potential variation impressed on the capacitance. To make the above point clear, the voltage appearing across the resistor terminals will be denoted by E'. Then

$$E' = IR = R\frac{dQ}{dt}$$

But since Q is related to C and E by the relation

$$Q = CE$$

it follows that

$$E' = IR = R\frac{dQ}{dt} = CR\frac{dE}{dt}$$

To illustrate the importance of the foregoing consideration a typical antenna, say 100 ft. long and 50 ft. high will be considered. A capacitance of 170 micro-micro-farads would be representative of such an antenna. Atmospherics of as much as 10,000 micro-seconds duration can occur, and this figure will be used as a maximum. To produce an RC time constant just equal to this figure (RC = 10,000 micro-seconds) with 170 micro-micro-farads capacity, a resistance of about 60 megohms would be required. Therefore, even though a measurement of $\frac{dE}{dt}$ considerably complicates interpretation of data, it might appear that this measurement would be the most practical one. Other fundamental problems concerning a study of atmospherics are choice of observing equipment, design of amplifiers when necessary and method of recording observed atmospherics.

An outline of the experiments of Appleton, Watt and Herd on the nature of atmospherics in England and Africa from 1922-24 will now be presented.[3] Although these experiments were conducted in the early days of radio, they nevertheless represent one of the most accurate and complete investigations in the field of atmospheric research up to the present time. Their method of solution of the problems outlined in the preceding paragraph will be given. This will be followed by a description of the author's method, demonstrating the advantages of lower cost, greater flexibility and greater ease of operation made possible by more modern equipment and technique.

Appleton, Watt and Herd were quite aware of the advantages of a system which would measure the E variation of an antenna directly.[4] Consequently, they set out to construct an antenna physically long enough to produce a quite appreciable capacitance such that the resistance of the measuring equipment connected from antenna to ground would not have to be unreasonably high. Use of a long antenna also increased the amount of voltage pickup, thus requiring less amplifier gain in subsequent circuits. The antenna which was used had a length of 500 metres and an effective height of 15 metres. Capacity to ground measured 2770 micro-micro-farads. For measurement of E variation directly, the input resistance of the measuring equipment was kept at 10 megohms, resulting in a time constant of about 28,000 micro-

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[3] Appleton, Watt and Herd, <u>Loc. Cit.</u>

[4] <u>Loc. Cit.</u>

seconds which was considered adequate for atmospherics of up to 10,000 micro-seconds duration. A great deal of difficulty was experienced in keeping the leakage resistance of the antenna insulators high enough so as to have negligible effect on the time constant of the antenna circuit. Special sulphur insulators were finally produced which were moderately satisfactory in the above respect.

The remainder of the equipment consisted of amplifiers and an oscilloscope. Since the atmospherics were amplified at their fundamental frequencies, direct coupled amplification was necessary for proper frequency response. Two stages of amplification were included with switching provided to allow either two stages, one stage or no amplification preceding the oscilloscope. In some cases of storms near the observing station the long antenna had sufficient voltage pickup so that it could be connected directly to the oscilloscope deflection plates. For signals of medium strength, one stage of amplification with a voltage gain of 18 was switched in the circuit. For the weak signals both stages were utilized with a total gain of 300.

The first series of observations with the above equipment was made in 1922. At that time practical linear oscilloscope sweep circuits were not in existence and a sine wave sweep was used. This type of sweep, according to the report, complicated interpretation of data to such an extent that all such data taken was considered unreliable.

In 1923, however, a linear sawtooth sweep system was developed, and all data taken in 1923 and 1924 was considered to be quite accurate. Altogether, 5,674 waveforms were recorded in the "best set" of data. A representative sample of the method of classification of these waveforms is given in Appendix I. All the above measurements were of $\frac{dE}{dt}$ rather than E, due to difficulties of various kinds encountered in keeping the equipment in satisfactory condition to read E directly. All such readings of $\frac{dE}{dt}$ were useful mainly in the determination of pulse duration and amplitude, being difficult to delineate into exact waveforms. They were, however, classified according to general types as shown in Appendix I. This method of classification of the usable waveforms according to types, however, would seem to be satisfactory enough to be adopted as an IRE standard. The method of recording used was simply that of sketching the waveforms from the observation oscilloscope by hand.

While the above described method served as a valuable guide, it was not directly applicable to the present experiment for a number of reasons. It should be remembered that the method was evolved at a time when tuned receivers were still in the experimental stage. However, some very significant remarks were included in the conclusions of this report concerning a type of "fine structure", which was associated with the phenomena. This peculiar "fine structure" was recognizable with only a short visual inspection of the oscilloscope. It was definitely associated with autumnal storms in England, and even more pronounced in a second group of observations made on the dark storms of Africa.

In order to aid in identification, a directional, rotatable antenna seemed quite necessary for our work, particularly on nights when other storms were present. This would be the only way to guide the tracking system toward the general tornado direction. An antenna such as was used by Appleton, Watt and Herd, namely a long inverted "L", would be directional and would have directivity along one fixed axis.[5] Furthermore, it would be very expensive to construct. On the other hand, an antenna, such as a loop, which was small enough to be rotated would by comparison suffer greatly in sensitivity, and a considerable amount of amplifier gain would be necessary to make up the deficit. Amplification of atmospherics at their fundamental frequencies can be accomplished only by a direct-coupled amplifier. A high gain direct-coupled amplifier is both difficult to build and unstable in operation. For these reasons it was decided that satisfactory accomplishment of the desired objectives could only be accomplished by the employment of a higher frequency receiver of either the Tuned Radio Frequency or Superheterodyne type. Utility was here made of the fact that although most of the energy emanating from lightning discharges lies in a relatively narrow band, there are, nevertheless, frequency components extending well up into the ultra-high frequency range. Whether the modu-

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[5] Appleton, Watt and Herd, Loc. Cit.

lation envelope of a particular higher frequency band would correspond exactly to the basic lightning stroke waveform was subject to speculation. All evidence available indicated that this was, at least roughly, the case. Besides, to satisfy our objective it mattered not so much that an exactly true waveform of the lightning would be gained. The prime purpose was to ascertain if there would be any essential differences between lightning waveforms and ordinary atmospheric waveforms within the frequency band used. Sufficient gain with adequate bandwidth would then be only a matter of proper receiver design.

It is true that positive and negative sense is lost in changing to this type of reception; however, Watt, Appleton and Herd in their general conclusions attached no significance whatever to this feature as far as identification of types of storms was concerned.[6]

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[6] Appleton, Watt and Herd, Loc. Cit.

CHAPTER III

DESIGN AND MODIFICATION OF RECEIVING EQUIPMENT

Again the available war-surplus equipment was examined as a possible source of apparatus to be used on the project. Conceivably, much time could be saved by modifying such equipment rather than designing and building a receiver specifically for this purpose. It was desirable that the receiver cover the same frequency range as that employed in the tracking system being developed for this project and also that it be directional. The Type BC-433G Radio Compass Receiver used for the tracking system again appeared to be most suitable.

As designed and built, this receiver had a bandwidth measured at the half-voltage points of 3.5 kilocycles. An assumption was made, which was later verified, that practically all the lightning bursts would be 1000 micro-seconds or longer in duration. Thus, if the receiver were made to pass a 1000 micro-second square pulse with negligible distortion, satisfactory reproduction would be assured. From pulse theory and from considerations of the Fourier analysis of a square pulse, it is found that the bandwidth of the amplifier used should be sufficient to include the fifth and preferably the seventh harmonic of the fundamental pulse frequency. Thus if the fundamental is 1 kilocycle, a bandwidth of 5 kilocycles would be sufficient, but 7 kilocycles would be slightly better.

For the benefit of any of those who might desire to modify this receiver for a similar purpose, an account will be given of some of the difficulties involved. As a matter of fact, if some of these difficulties had been evident at the outset, it would perhaps have been more profitable to design a completely new receiver. However, after modification, the receiver used gave very satisfactory results.

The narrow bandwidth of the original receiver was due primarily to the intermediate frequency amplifier. Such sharp selectivity was not surprising at a center frequency of 145 kilocycles. Only one stage of amplification was employed, but both the input and output transformers had high Q primaries and secondaries and were somewhat undercoupled, i.e., $KQ < 1$. A logical first step in broadening the bandwidth appeared to be an increase of the coupling. The input transformer was disassembled and found to be capacitively coupled. Inductive coupling had been effectively eliminated by enclosing the coils in powdered iron forms, and inductive tuning had been incorporated by use of powdered iron slugs. However, in comparison to the mass of powdered iron which enclosed the coils, the tuning slug in the center was rather small and effected a very limited tuning range. Coupling was increased by adding more capacitance in parallel with the coupling condenser. As is well known, an increase in this type of coupling shifts the center of the resonant frequency in the range of $KQ > 1$. With the extremely limited tuning range mentioned above, the transformer could not be restored to correct center frequency with the fixed tuning capacity present. Attempts were made to change the tuning capacitance by the proper amount. Again, the limited tuning range of the slugs gave very little leeway on choosing the proper capacitance. This cut-and-try method of soldering on a different condenser, re-assembling the transformer, then connecting it into the receiver and measuring center frequency was finally abandoned. A Q-meter or its equivalent would have solved the problem but none was available.

A commercial, capacitively tuned, inductively coupled 175 kilocycle transformer was then modified and used to replace this transformer. The coupling was adjusted to give just a slight dip at center frequency.

The second intermediate frequency transformer was found to be somewhat more flexible and to possess a greater tuning range. In conjunction with the input transformer replaced as above, the second transformer was stagger tuned by carefully adjusting resonant peaks of primary and secondary to coincide with the peaks of the input transformer. A frequency modulated signal generator was used for this alignment. The signal generator frequency was "swept" through the intermediate frequency amplifier band at a rate which was synchronized with the horizontal sweep of an oscilloscope. The output of the detector was applied to the vertical plates of the oscilloscope in order to obtain a visual picture of the intermediate frequency response.

When modification was complete, the receiver had an overall bandwidth of 7.5 kilocycles measured at the half voltage points. Square wave response was also checked to make sure of fidelity in reproduction of lightning waveforms. A signal generator was modulated with a square wave generator, this signal being fed through the whole receiver. A 1 kilocycle pulse came through unaltered, and in fact noticeable rounding of the corners occurred only after the frequency was raised to around 2.5 kilocycles.

One question which might naturally arise concerning modification of the receivers would be that concerning the use of circuit loading to reduce Q in order to obtain an increase in bandwidth. This was tried without success. The reason evidently lay in the undercoupling of the transformers. Under certain conditions of undercoupling, the application of loading reduces Q and with it the coupling KQ to such an extent that it overcomes the advantage of flattening the resonance curves.

With the intermediate frequency amplifier completed, the modification of the remainder of the receiver was fairly simple. The 400 cycle power transformer was replaced with a 60 cycle transformer and it was found that the power supply choke and filter condensers were adequate. The band switch which had operated from a 24 volt motor was modified to permit manual bandswitching. Output of the detector was direct-coupled to the oscilloscope to improve the low frequency response.

DESIGN AND MODIFICATION OF PHOTOGRAPHIC EQUIPMENT

As mentioned previously, the duration time of a tornado is so short that a very rapid method for observing and recording the waveforms from the oscilloscope screen is an absolute necessity. Accordingly, a 5LP2 long-persistence tube was ordered for a laboratory model 208 Dumont oscilloscope to aid in this observation and permit some tracing of the wave forms on thin tracing paper.

However, it appeared very likely that considerable analyzation of basic waveforms and familiarization would be necessary before rapid visual tornado identification would be possible. For such detailed analysis a photographic record provides a more exact and permanent method. In general, the most satisfactory recording of random transients is accomplished photographically with a "continuous film" camera. This is a "shutterless" type of camera wherein the film is drawn by at a uniform rate of speed. The motion of the film is at right angles to the oscilloscope signal deflection to be recorded. No sweep is used on the oscilloscope since the motion of the film relative to the oscilloscope effectively provides the necessary sweep action. Thus, the film might be drawn vertically with the signal to be observed applied to the horizontal oscilloscope plates. The time base is extremely linear when the film is moved by a constant speed motor. The recorded transients are displayed successively along the length of the film with no overlapping or obliteration due to occurrence between sweeps or at the end of a sweep as is the case for regular oscilloscope displays. Practicality and economy ruled out such a method, however, for this particular application. Film speeds up to 30 ft. per sec. have been attained with this type of camera but both the first cost of equipment and subsequent cost of film are very great. At 30 ft. per sec. a 1000 micro-second pulse would be $\frac{1}{1000} \times 30 \times 12 = 0.36$ inches in width which would be satisfactory. At this speed, however, a 100 ft. roll of film would only last about 3 seconds. At a tenth this speed the image would be only 0.036 inches, a size which would lack detail due to the grain size of the usual commercial film. Furthermore, use of a 100 ft. roll in 30 sec. would be quite costly in terms of the amount of data recorded.

The duration of an oscilloscope trace is too short, even with long persistence tube screens, to permit manual opening of a shutter in time to catch a desired waveform. A movie type framing camera was chosen as the best compromise. Since refinements such as a fast lens increase rapidly in cost with increased film size, a 16 mm size was selected. Previous experience in recording other oscillographic data had proved this size to be quite satisfactory. This experience had also shown that a lens of f 1.5 speed would be necessary. A 16 mm aircraft type war surplus camera with f 1.5 lens was obtained and modified for this purpose. In order to have the field of view include essentially the screen of the oscilloscope and focus at a convenient distance of 2 to 3 feet from the oscilloscope, it was necessary to bore out the lens mount, build a new mounting ring, and set the lens in closer to the film. The camera was driven by an electric motor powered from batteries. By using Super XX film and a setting of f 1.5 on the camera it was possible to reduce the intensity of the oscilloscope sufficiently to prevent burning of the screen when operated over long periods of time.

The framing camera method of recording has one main disadvantage. Quite a few of the random transients occur either too close to the end of the sweep or else between sweeps. However, previous experience from oscillographic recording had shown that a good representation is obtained from the random bursts which occur during the sweep.

Medium persistence oscilloscope tubes were used for photographing, the green P1 being used for most of the data with a white P4 employed for comparison in some cases. A very short persistence blue tube designated as Type P5 is usually used for photography, but its chief advantage is for continuous film work. In such an application the decay of light must be rapid enough so that movement of the film relative to the cathode ray spot does not produce the effect of blurring. It should be noted that with a framing camera no such effect is possible. The film is stopped during the time the exposure is being made. Aside from a slight "spreading" effect and "double exposure" effect, the trace on a long persistence tube could be photographed with results comparable to medium and short persistence tubes.

The "spreading" effect is due to a screen coating which is a combination of fluorescent and phosphorescent material. Once a particular area or line has been energized on this surface, quanta may be radiated to neighboring particles at the edge of the affected area. Re-radiation from these particles may then emit light and in this manner an effectively larger light source can be produced. This produces a coarser line, but the effect is still small when compared to the size of the film grain. The "double exposure" effect is caused by the ability of the long persistence tube to retain images long enough to be photographed on several successive film frames. The latter effect complicates identification of individual waveforms to such an extent that it is expedient to use a different oscilloscope tube for photography from that used for direct viewing.

CHAPTER IV

RECORDING OF DATA

Actual observations on atmospherics began June 22, 1948. Statistics show that June and July are normally months of high tornado activity, having very long days during which a large amount of solar energy accumulates. The Weather Bureau at Ponca City, Oklahoma, was contacted, and the observers there agreed to immediately relay by telephone any tornado information which had been reported to them. With advance warning extra data and observations could be taken during the time of tornado activity, so that identifying characteristics of tornado atmospherics could be studied in detail until visual recognition would be possible almost immediately from the oscilloscope.

The first data, taken at 5:00 P. M., June 22, was mainly for photographic test purposes. There was, however, a thunderstorm of the common variety about 5 miles distant to the Northwest. This film was developed, and proper settings of the camera and oscilloscope were obtained. For subsequent observations a definite procedure was established. A title block was printed and photographed before each set of observations. The title displayed the date and hour, type of oscilloscope tube used, and positions of the directional antenna. In actual recording, blank spaces were left between groups of data corresponding to the different antenna positions. Word descriptions were also written up with dates and times corresponding to those on the title block. Recordings were made in the order of antenna loop horizontal, then in the direction of the storm and then perpendicular to the storm direction. As soon as a barometer could be obtained, barometric pressures were recorded in terms of the normal with the storm descriptions.

Considerable data was recorded on all the thunderstorms which occurred. There were two reasons for this procedure. First, the storm might turn out to be of tornado type even though not reported as such by the Weather Bureau, since their communications could be cut off by just such a storm. Second, the careful scrutiny of the waveforms from the lightning of an ordinary storm should provide the familiarization necessary to recognize waveforms of a different type. A standard time base of 5000 micro-seconds was used on the oscilloscope for all measurements. At the frequency used the sawtooth sweep time base was quite linear. With the exception of some film taken prior to July 3, all film was processed negative. This procedure gives much better detail and is considerably easier to read than positive prints.

An account will be given of each of the storm observations. These observations were recorded as an experiment to determine whether or not general weather conditions preceding a tornado might be definite enough to warn an operator of its possible occurrence.

June 24, 1948. 9:15 P. M. Storm to North. Day had been hot, humid and still. Recordings made with loop horizontal, then to north, then to east. At 11:20 P. M. lightning was to NE. Last observation and recording made at 1:45 A. M., June 25. Loop antenna sequence--horizontal, NE, NW. Reports indicated an ordinary thunderstorm.

June 26, 1948. 1:00 P. M. Weather Bureau relayed reports of a tornado just South of Tulsa. Non-directional reception used first in recording. Then directional EW, then NS, then horizontal. Lightning waveforms did not appear any different from a visual observation than on preceding days. Reports were unconfirmed the next day.

June 26, 1948. 11:45 P. M. Storm to NW of ordinary appearance. Light winds, rain next morning. Recording sequence--loop horizontal, NW, NE. Reported as ordinary thunderstorm. Barometer normal.

For all the following observations the loop sequence was: horizontal, then in the storm direction, then perpendicular to this direction.

June 27, 1948. 9:00 P. M. Storm to NW with light winds. Ordinary thunderstorm. Barometer - 0.05 inch low. At 10:25 P.M. another recording was made. Storm was then closer but of same appearance.

<u>July 3, 1948</u>. 8:10 P. M. Day had been warm and humid with barometer about 0.1 inch low. Clouds in NW when recordings were made. No lightning was visible, but clouds were definitely of storm type. Then at 11:00 P. M. the clouds moved to due north with moderately fresh winds. Reports the next day included no tornadoes in the vicinity.

<u>July 5, 1948</u>. 1:50 P. M. Storm came rather suddenly from south. High clouds and cold wind typical of hail, but no hail was formed. Turned out to be an ordinary thunderstorm.

<u>July 7, 1948</u>. 11:00 P. M. Storm to NE. Had been hot, still and humid with barometer 0.2 inch low. No tornado developed, however.

<u>July 9, 1948</u>. 1:00 P. M. Storm and lightning almost directly overhead. Had been hot, still and humid. The storm formed very rapidly. No tornado.

<u>July 14, 1948</u>. 9:00 to 10:00 P. M. No film on hand so waveforms were sketched from the long persistence oscilloscope. Barometer had been 0.3 to 0.4 inches low all day. Day had been hot but not so humid and still. Lightning was so abundant the sky was almost continually lighted. The observed waveforms were the same essentially as for other observations. No tornado.

<u>July 21, 22, 23, 1948</u>. All around 8:00 P. M. Ordinary thunderstorms in vicinity. Lacking film, visual observations were made. No essential difference in waveform characteristics.

CONCLUSIONS

It would appear from the visual observations that conditions which should favor the occurrence of a tornado most often result in ordinary thunderstorms. However, since no tornado of significant proportions occurred during the whole month of July, this should be regarded as a most unusual year. The whole area was favored with abundant rainfall during the latter part of June and most of July. This rainfall proved to be effective in breaking up the tornadoes which normally would have been present.

A number of very interesting and significant results were obtained by a comparison of atmospheric waveforms photographed during the present experiment with "sketches" made by Appleton, Watt and Herd during their somewhat similar research.[1] Before going into a comparison of results, an explanation should be given concerning the sketches taken by these men and the reason such sketches were made. During the course of their observations a particularly striking type of atmospheric waveform was noted from time to time, containing a series of ripples which they termed "fine structure". This fine structure seemed to be abundant in some storms and almost entirely absent from others. By keeping notes, the fine structure was finally found to be associated with autumnal storms in England. A number of sketches

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[1] Appleton, Watt and Herd, Loc. Cit.

were made of these interesting waveforms and included in a report on the experiment. Since no photographic equipment was used by Appleton, Watt and Herd for recording data, visual observations of an oscilloscope trace were made and sketched freehand on a piece of paper.[2] Accordingly, their data would vary somewhat from a true picture, but would nevertheless portray the essential nature of fine structure. Also, as regrettably remarked in their report, the sketches which were actually made are by no means representative of fine structure in general, since they were forced by practical difficulties to use the $\frac{dE}{dt}$ method of recording (mentioned in the summary of their experiment) most of the time instead of a direct E method. Only the direct E measurements were suitable for depicting fine structure.

During examination of waveform photographs from the present tornado experiment a large number of waveforms were discovered which also contained fine structure. Since this fine structure appeared to resemble the "sketches" shown in Appleton, Watt and Herd's report, a detailed comparison was undertaken.[3] This study revealed that a great many waveforms taken from the two experiments bore a striking similarity. Figures 1 through 5 are included in this report as representative samples. In each

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[2] Appleton, Watt and Herd, Loc. Cit.

[3] Loc. Cit.

figure the "sketches" are denoted by "b" and photographic reproductions from the present experiment by "a". The photographic reproductions are exact representations while the freehand sketches would tend to vary slightly from true waveforms. However, this variation is of no consequence in the present comparison.

Both photographs and sketches are recorded on a 5000 microsecond time base for all figures shown. Therefore, a direct comparison can be made of time duration of the atmospherics as well as actual wave shapes. On the basis of a time duration comparison, Figures 1, 2, 3, and 5 correspond quite well. In Figure 4 the sketched waveform "b" is seen to have considerably greater time duration. Also, in Figure 4, an extra notation "a'" is introduced to denote a waveform resembling "b" less closely than "a", but still of the same general shape.

It should also be pointed out that the oscilloscope was sweeping from left to right in the case of both "a" and "b". Correct time sense is preserved by considering the time base or sweep as beginning on the left side when viewing the figure in the normal manner. For instance, the wave shapes of Figure 2 have a very steep "rise time" with a somewhat slower "oscillatory" decay. To further facilitate comparison, the downward deflection of both "a" and "b" should be explained. As pointed out previously, the detector output of a tuned receiver cannot preserve the polarity of an atmospheric disturbance, since it furnishes only a modulation envelope with whatever fixed polarity the detector is arranged for in a particular receiver. Furthermore, some oscilloscopes display a positive signal as an upward deflection while others furnish an "inverted" or downward deflection for a positive input signal. In the present case the BC 433G receiver used in conjunction with the Dumont 208 oscillograph resulted in a downward deflection for all atmospherics impressed on the receiver antenna. In the case of the "b" figures, however, it will be recalled from a previous discussion that either positive or negative deflections were possible depending on the polarity of the atmospheric impressed on an antenna. Appleton, Watt and Herd arranged their equipment so that a negative atmospheric gave a downward deflection while a positive atmospheric gave an upward deflection.[4] Practically all the atmospherics which they recorded were of the negative type so that all "b" sketches were chosen from the negative group and are presented in their correct sense. Therefore, in comparing "a" and "b" types the only discrepancy which might exist lies in the possibility that "a" might have been either a positive or negative atmospheric and therefore might in some cases need to be inverted for true comparison. As was just mentioned, however, practically all atmospherics are of the same polarity. The sweep

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[4] Appleton, Watt and Herd, Loc. Cit.

sense of left to right and the downward deflection was carefully preserved in all photographic processes necessary in final reproduction of the figures. Slight rotation of the oscilloscope tube before photographing which produced the slanted base line evidenced in the figures aided in this respect.

Figures 2 "a" and 3 "a" as well as other photographs contain double waveforms caused by two sweeps within the time of film exposure. This disadvantage was mentioned earlier as inherent with a sweeping oscilloscope, but it rarely causes undue confusion of individual waveforms.

Figure 6 is included to show a type of mirror symmetry or actually a contrast of waveforms. In both experiments many cases were found of waveforms having a very steep rise time (denoting a rapid voltage buildup) followed by a slow decay such as Figure 6 "b". The present experiment, however, included several of Type 6 "a", having a slow buildup and very steep decay. No such waveform was found in the older experiment. Figure 7 includes the remainder of the sketches taken by Appleton, Watt and Herd.[5] Note that only one of all these samples was a positive deflection. Figures 8 through 19 are more actual photographs of particularly outstanding waveforms filmed from the present experiment. Of this group, Figures 12 and 13 are distinct new

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[5] Appleton, Watt and Herd, Loc. Cit.

types compared to any obtained by Appleton, Watt and Herd, though not of such striking contrast as Figure 6.

The photographs in all these figures were enlarged from 16 millimeter film and have lost considerable detail as a result of several intervening photographic processes. This was done for the purpose of report presentation only, since a magnifying viewer used with the original 16 millimeter film negatives displays a sharper image and is thus more satisfactory for experimental viewing and comparison.

A further and more complete comparison of the two experiments is shown by tables in Appendix I. This comparison is based on the method of tabulation and study used by Appleton, Watt and Herd.[6] Sketches at the top of each column denote general waveshapes, disregarding ripples. Since these sketches are for designation of types only, they are shown inverted from actual oscilloscope presentation. To further explain the type designation, consider sketch "A". This is a sharp peaked waveform with sides symmetrical about the peak. Figure 4 "a" may be referred back to as an example of this type. Sketch "B" is by the same system a rounded symmetrical type and would correspond to Figure 4 "a" disregarding ripples. It should be remembered, however, that the figures in this report are unusual types, and

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[6] Appleton, Watt and Herd, <u>Loc. Cit.</u>

the bulk of waveforms from which Appendix I is tabulated are of smooth appearance, containing very little ripple. Proceeding along the various types, "C" is a sharp peaked waveform with the peak displaced to the left, or more precisely this type has a steeper rise time than decay time. An extreme example would be Figure 6 "b". Type "D" is a sharp peaked waveform with slow rise time and faster decay of which Figure 6 "a" would be an extreme example. Type "E" is a rounded form of steeper rise than decay and Type "F" is a rounded form of slower rise and faster decay. In the left column of Appendix I each set of data is identified. Set I is a tabulation made by Appleton, Watt and Herd composed of figures totaled and averaged for a large number of storms.[7] Since all their data was taken in this manner, no comparison can be made between individual storms. In the present experiment the author was of course interested in individual storms and sets 2 and 3 are accordingly representative of a particular storm for each set.

Under each type of waveform is tabulated the number of this type and what percentage this number is of the total. Sets 2 and 3 immediately reveal a striking similarity of percentages, which indicates the homogenity prevalent for all data taken during the present experiment. Further comparison of Sets 2 and 3 with Set 1 indicates a similarity quite close considering the very

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[7] Appleton, Watt and Herd, Loc. Cit.

different conditions under which the two entirely separate experiments were performed. These results indicate that even if a tornado observer were not able to recognize tornado waveforms instantly from visual observations, he might still be able to sketch a number of samples and figure percentages in order to recognize unusual storms.

At the time each set of data was recorded on a particular storm, the directional antenna was pointed first toward the storm; then rotated so as to have the null toward it; then the loop was placed in a horizontal plane, with markings to identify each such sub-group of data. No essential difference in waveform was noted between any of the three positions, except the horizontal position appeared to cut out distant reception. Lack of difference between the vertical maximum and null directions was not discouraging, however, in view of the fact that as shown in Appendix I, ordinary thunderstorms contain essentially the same waveforms. Utility of directional properties could still be made in distinguishing tornado direction from thunderstorm direction provided there were sufficient difference in the waveform characteristics of the two storms. Since the recording apparatus and method of tabulating data have been established, there remains only the recording until such time as a tornado might occur to verify, or possibly disprove, the identification method. The recording apparatus will be left in operation and observations made on future storms. "Secondary" types of tornadoes sometimes occur in the fall and special attention has been paid to this period of likely activity. No significant tornadoes have occurred to date in this vicinity.

Work is being continued on the phase shift and antenna problems. When this equipment is completed, it will be integrated with the identification equipment to form a complete station.

In conclusion, it might be well to point out some of the possible applications of thunderstorm and tornado identification and tracking, if such a system becomes workable. The most important use would, of course, be warnings to cities and towns in tornado paths, in time to save many lives each year. Then there would also be the important application of supplying information to power and telephone companies, enabling these companies to more accurately predict the location of possible line failures.

Figure 1

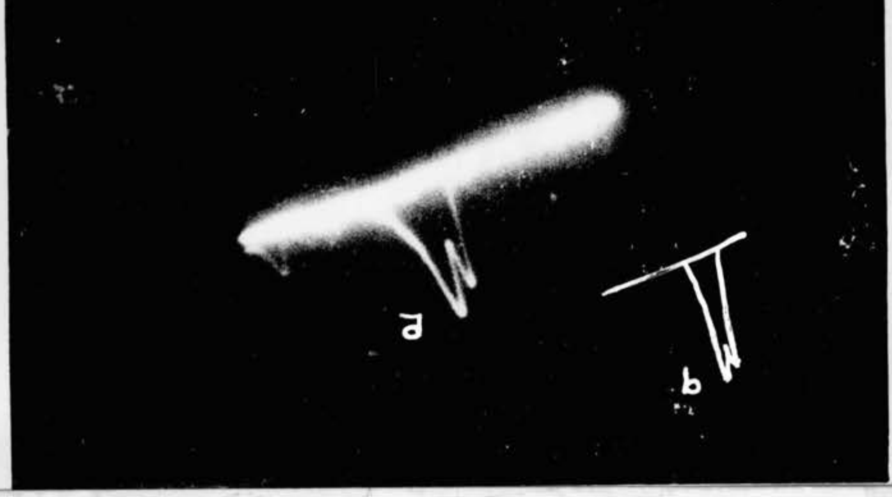
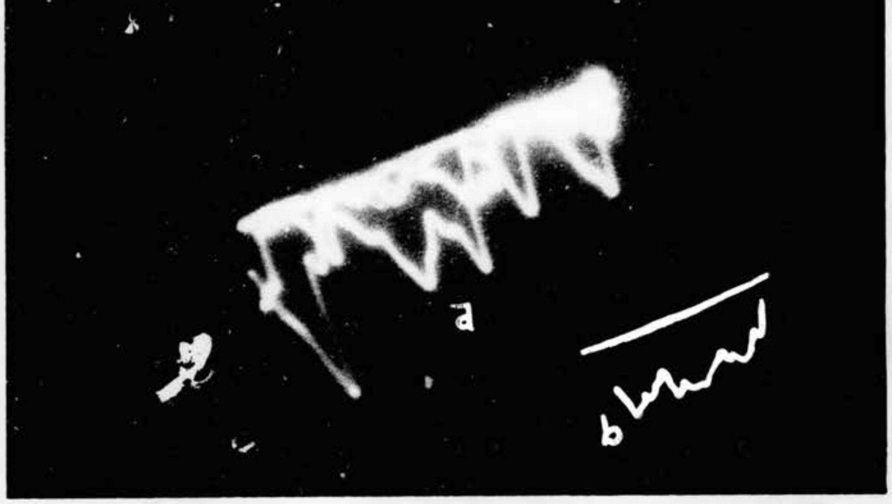


Figure 2

Figure 3



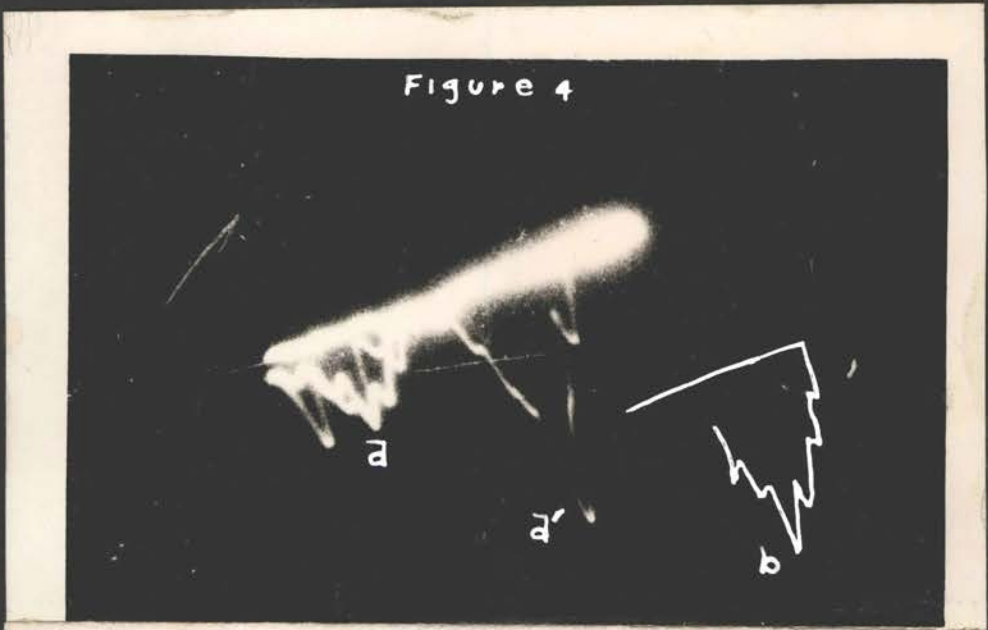


Figure 4

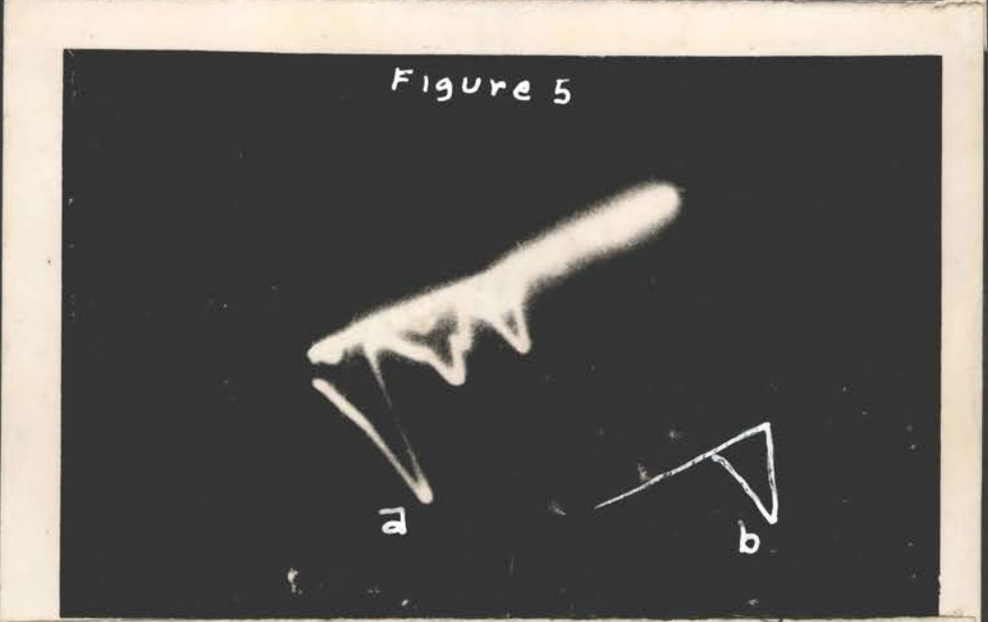


Figure 5

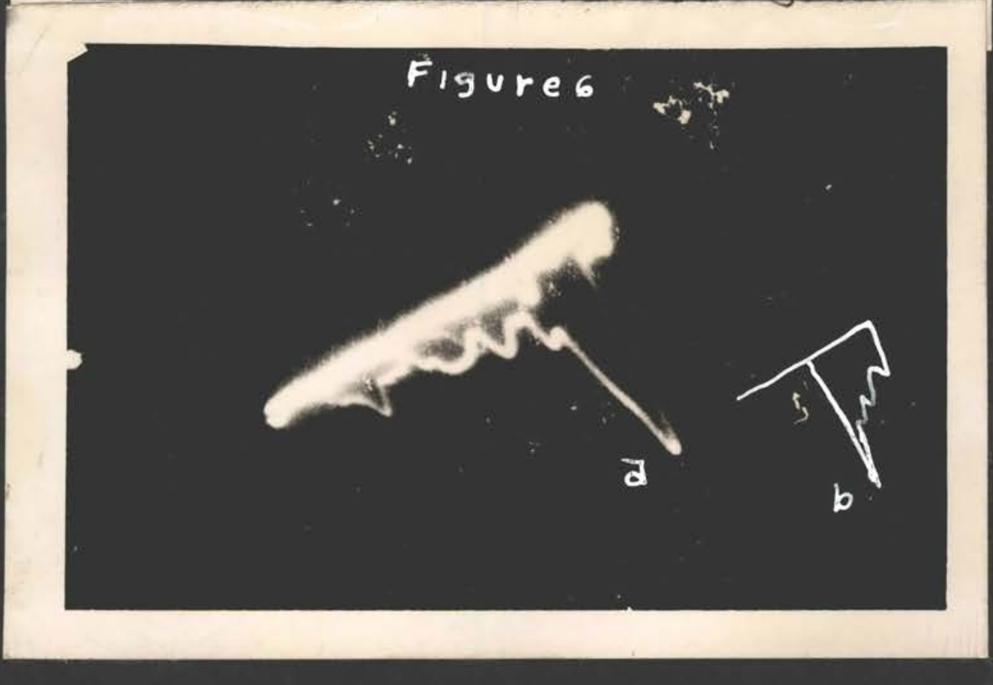


Figure 6

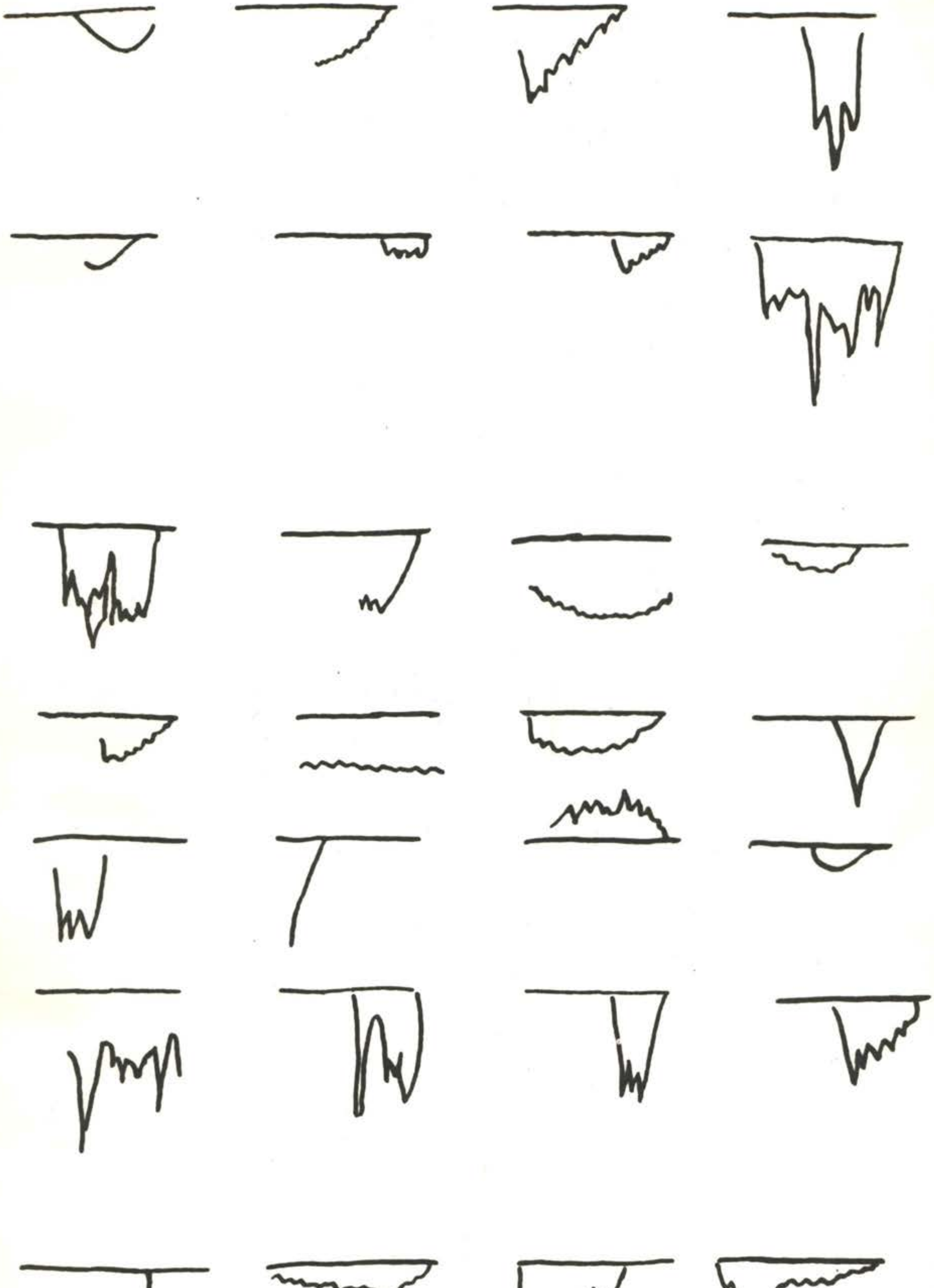


Figure 7

Figure 8

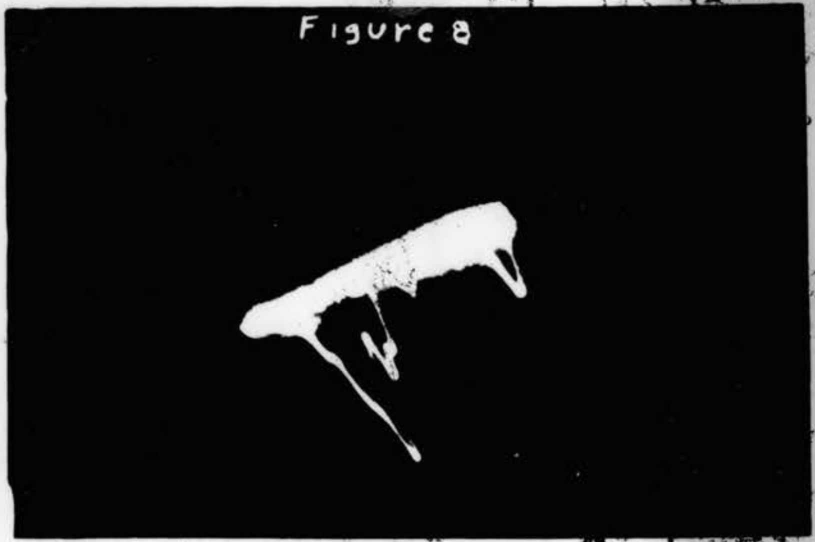


Figure 9

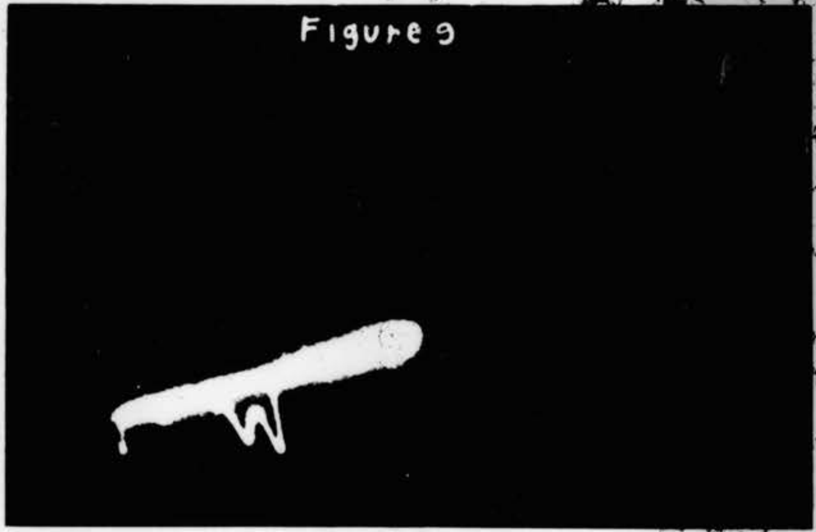
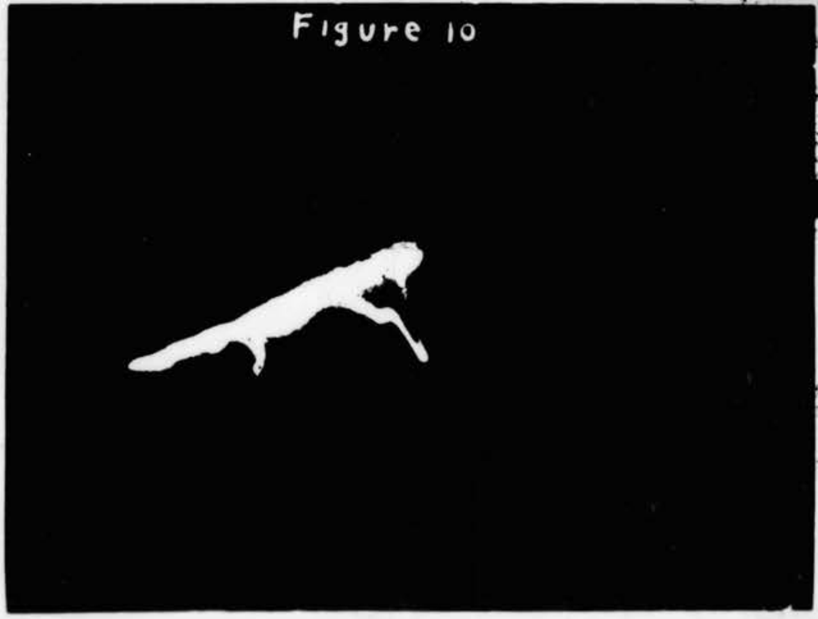


Figure 10



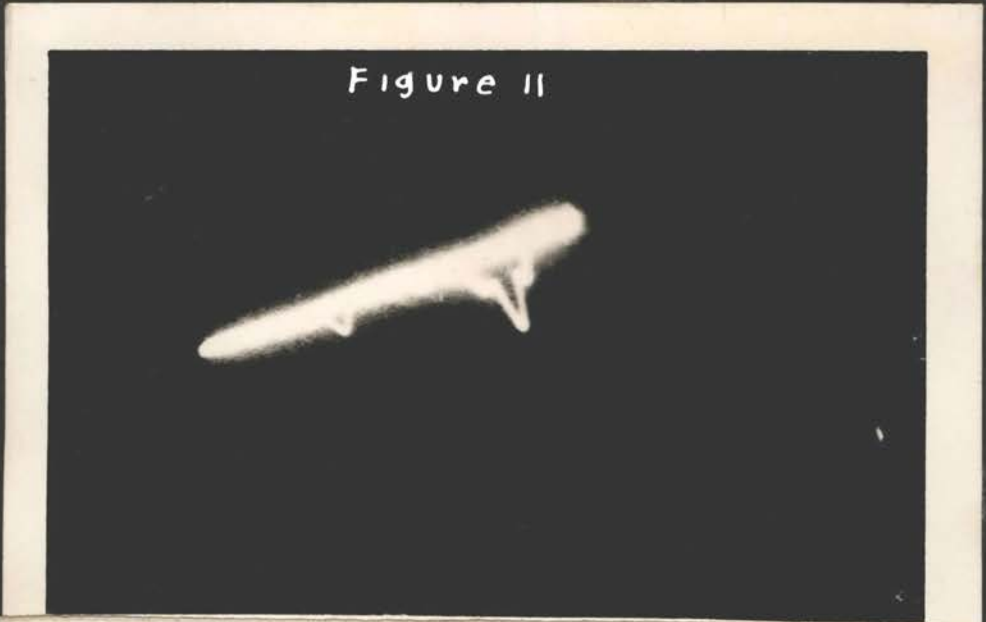


Figure 11

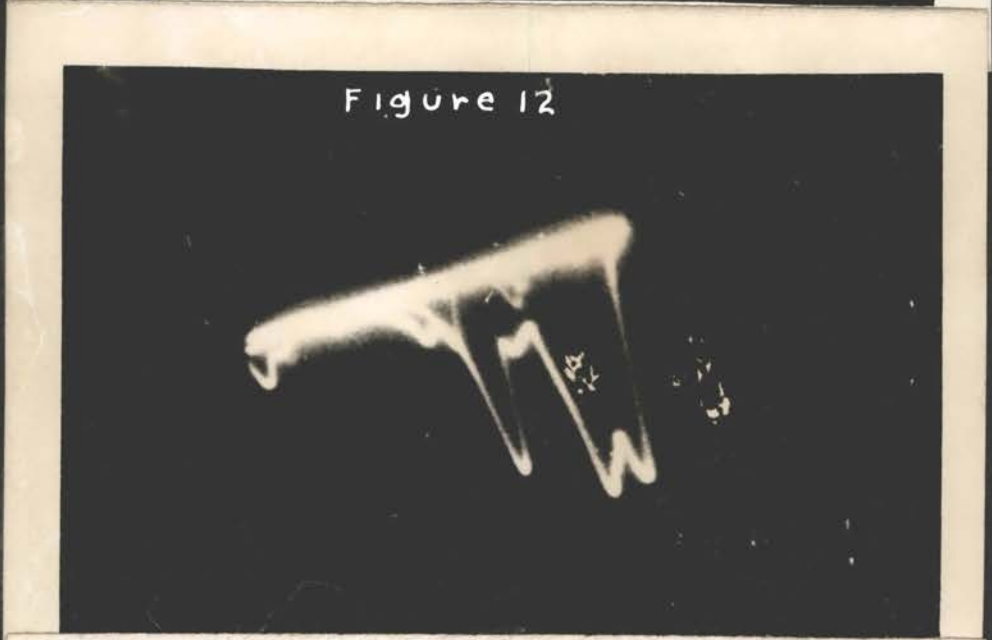


Figure 12

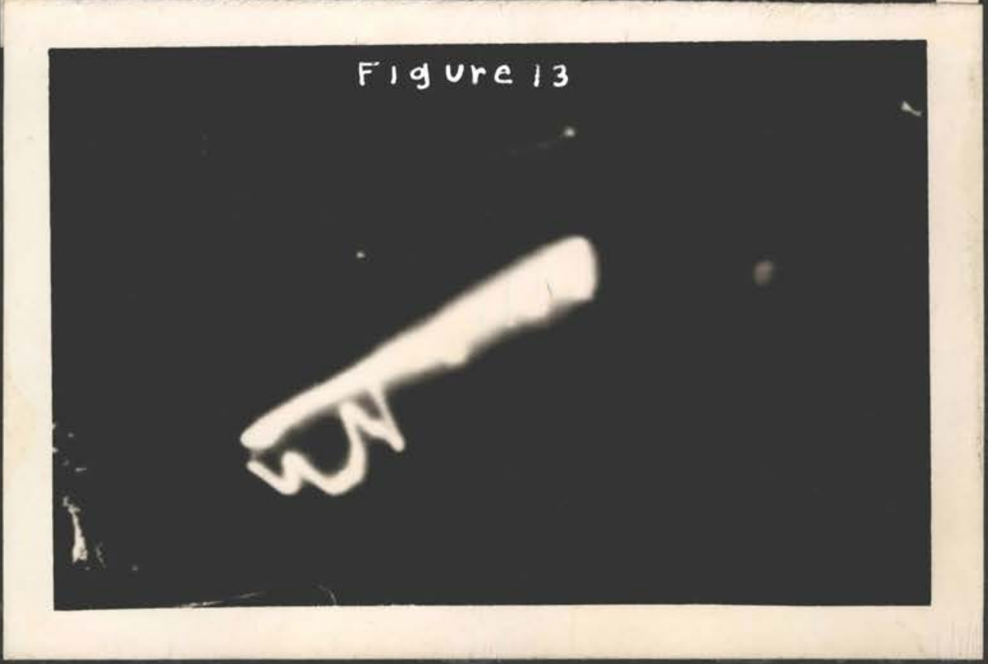


Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

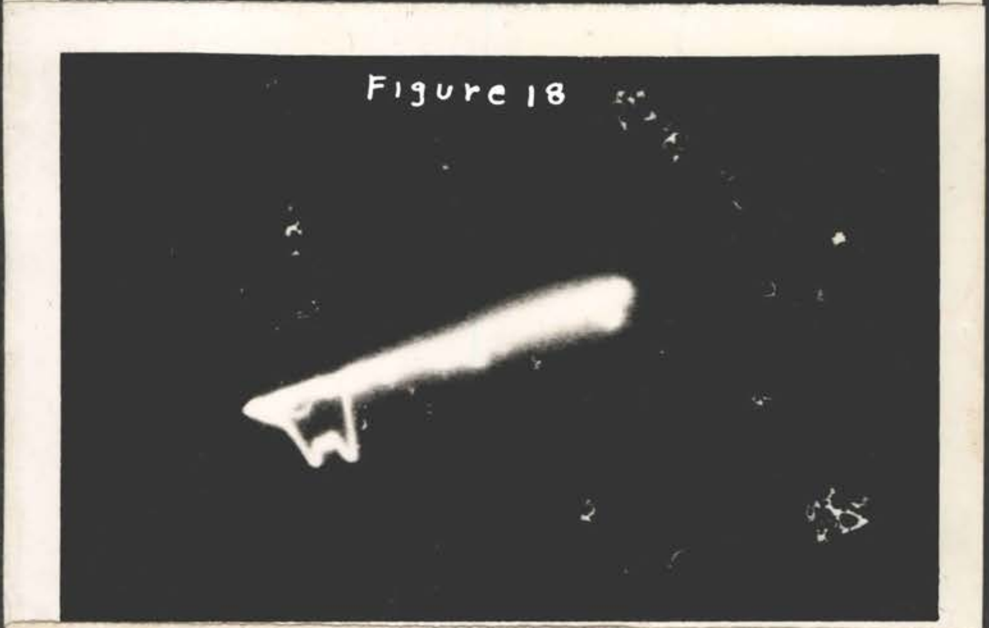


Figure 18

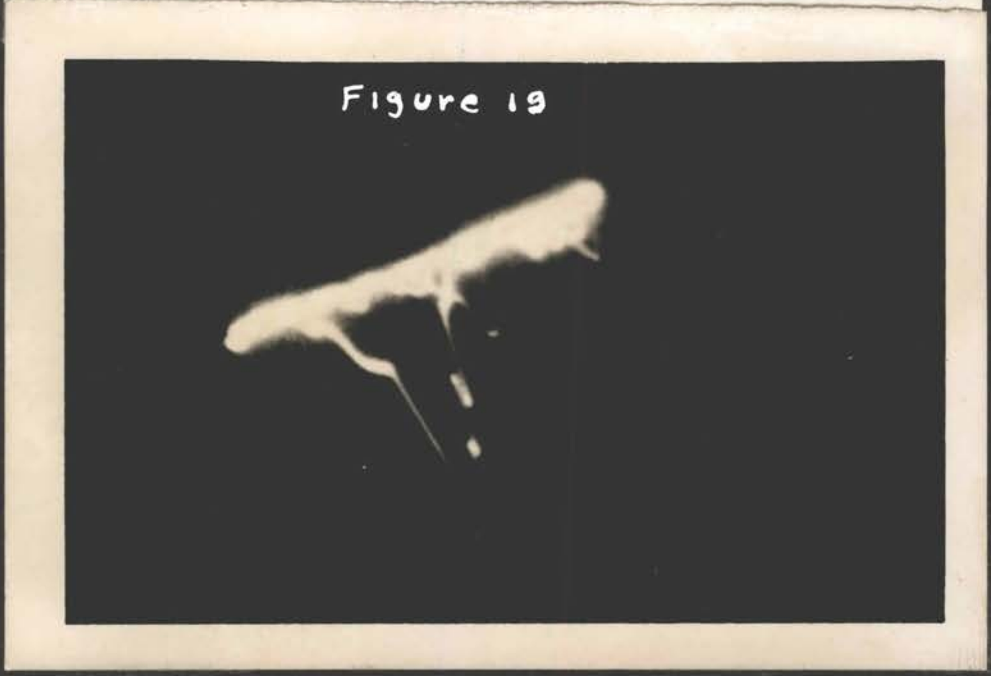


Figure 19

APPENDIX I

	A	B	C	D	E	F
WAVEFORM APPEARANCE:						
Set 1.						
EXPERIMENTER: Appleton, Watt & Herd						
DATE: 1922 - 1924						
NUMBER of Wave forms:	594	786	487	118	346	294
					TOTAL:	2,625
PERCENTAGE:	23%	30%	19%	5%	13%	11%
Set 2.						
EXPERIMENTER: Carl W. Miller						
DATE: July 3, 1948						
NUMBER of Waveforms:	108	112	40	140	28	44
					TOTAL:	472
PERCENTAGE:	21%	24%	8%	30%	6%	9%
Set 3.						
EXPERIMENTER: Carl W. Miller						
DATE: July 5, 1948						
NUMBER of Waveforms:	144	136	76	120	28	36
					TOTAL:	540
PERCENTAGE:	27%	25%	14%	22%	5%	7%

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- Patty June Howell -