

DEVELOPMENT OF ELECTRONIC EQUIPMENT FOR  
TORNADO DETECTION AND TRACKING

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DEVELOPMENT OF ELECTRONIC EQUIPMENT FOR  
TORNADO DETECTION AND TRACKING

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## PREFACE

Since 1949 Dr. Herbert L. Jones of Oklahoma A. and M. College has been the leader in the investigation of lightning activity in connection with tornadoes. A number of graduate students aided in the construction of the original tornado laboratory equipment. In January, 1952, the United States Signal Corps began sponsorship of the tornado tracking project and under this program I became project engineer. In this position, I have been responsible for the design, construction, operation, and maintenance of all the new equipment developed during this period.

A complete description of the tornado tracking equipment has not been presented before. As project engineer, I felt that it was my responsibility to prepare such a manuscript. An entirely complete analysis of the design and purposes of every item that has been developed in the past five years would fill several volumes. It is the purpose of this dissertation to present the theory and operation of all major equipment which is at present important to the tornado tracking laboratory. In an attempt to keep this dissertation to a satisfactory size, most of the simple undergraduate design problems have been omitted. The electronic system is so complex that even the bare essentials require many explanations for a complete description.

The development of the equipment for the tracking system required several years. The completed system was finally ready for operation during the 1956 tornado season. It was toward the middle of the season that the exact value of the tracking equipment was fully realized. The

results are gratifying to all concerned. Although the laboratory was successful in 1956 by tracking 90% of the tornadoes within the primary range of the laboratory, there is need for continued research.

So many persons have been helpful in the success of the tornado project and in the preparation of this dissertation that any list of acknowledgements would very likely be incomplete. Therefore, I will mention only a few. First of all I would like to thank Dr. Herbert L. Jones for his guidance as chairman of my graduate committee. I wish also to thank the other members of my committee, Prof. A. Naeter, Prof. Charles F. Cameron, Prof. Fremont Harris, and Dr. Clark A. Dunn, for their assistance. Miss R. Elizabeth Reynolds is deserving of my sincere thanks for her painstaking proofreading of the original manuscript. I owe a debt of gratitude to my draftsmen, Mr. Don Geurkink, Mr. Jack Lane, Mr. Frank Wright, and Mr. Rex Wenger, who helped prepare many of the schematic drawings. Thanks are also due to the Signal Corps for the sponsorship of the tornado project. Without its assistance the research would not have been possible.

The one person who is deserving of much appreciation and thanks is reserved for last. This one person is my wife, Anita, who painstakingly typed this dissertation while still maintaining our home in a wonderful manner.

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## CHAPTER I

### INTRODUCTION

One of the most evasive small scale factors of Nature is the electron, which has been utilized, if not all but conquered, by man. No matter how he may control the electron to do his bidding man still can not explain exactly the complete nature of the tiny being.

In order to formulate any idea which might explain a particular phenomenon, scientists must make measurements upon the object of their investigation. In the case of the tiny electron, all measurement techniques<sup>1</sup> fail when an attempt is made to localize its existence and observe its exact nature.

An evasive large scale product of Nature is the thunderstorm, which has been under observation of mankind for centuries. Yet, no one has a complete explanation for the phenomenon that closely accompanies the thunderstorm, lightning. Many surprising facts have been observed in connection with lightning, and many theories have been offered to explain them. Lightning photographs<sup>2</sup>, taken with a moving lens Boys Camera, have shown that a discharge which might appear to be a single stroke of fluxuating brilliancy is, in reality, composed of multiple strokes over the same ionized path.

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<sup>1</sup>David Bohm, Quantum Theory (New York, 1951), pp. 138-140.

<sup>2</sup>B. F. J. Schonland, The Flight of Thunderbolts (Oxford, 1950), p. 70.

These photographs also show that each cloud to ground discharge is preceded by a leader that erratically darts from the base of the cloud to the earth, and is followed by a return stroke from the earth back to the cloud over the same path.

Once Benjamin Franklin proved that the lightning discharge was electrical in nature, many measurements<sup>3</sup> were made to establish the magnitudes, directions, and durations of the currents and electric fields associated with lightning. The early measurements utilized crude equipment to determine the type of charges involved; for example, Leyden jars and electroscopes with pointed aerial charge collectors. At least one experimenter was electrocuted while making his observations.

In the case of more recent investigators, more elaborate equipment has been employed, and many measurements have been made from a distance. The fact, that a widespread electromagnetic field is associated with each lightning discharge, provides an excellent method whereby distant detection and measurements can be made upon existing thunderstorms. Because of the transitory nature of the thunderstorm, measurements cannot be re-made and verified; the first measurement is the final measurement, and many storms must be evaluated in order to draw any satisfactory conclusions. This fact is what sets thunderstorm measurements apart from the measurements of more permanent phenomena of nature.

The thunderstorm alone is not the sole center of scientific attraction, but rather the mighty tornado which is likely to spawn from one.

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<sup>3</sup>J. Alan Chalmers, Atmospheric Electricity (Oxford, 1949), pp. 1-10.



The electromagnetic radiation from the thunderstorm is utilized as a gauge to determine the severity of a given cell and to evaluate its tendency toward tornado activity. To maintain a 24-hour surveillance on this electromagnetic effect in order to be prepared in case that a severe storm should develop is a time consuming job. If it were not for the work of a few brilliant investigators, this type of surveillance would be required.

In January, 1951, the Bulletin of the American Meteorological Society published an article by Major E. J. Fawbush, Captain R. C. Miller and Captain L. G. Starrett entitled, "AN EMPIRICAL METHOD OF FORECASTING TORNADO DEVELOPMENT." These men found that a five-fold meteorological relationship must exist in order for a tornadic condition to prevail. By extrapolating the existing meteorological tendencies, they could forecast the probable time and locality in which these conditions might be simultaneously present and thus produce a tornado funnel.

This scientific finding represents a milestone in the quest for knowledge relating to the devastating tornado, and roughly corresponds in mental scope to the simultaneous solution of five differential equations. It was with the aid of this early warning method that a system of electromagnetic detection stations could be activated in time to obtain a complete record of the rise and decay of tornadic storm systems.

For sometime prior to this publication, Dr. Herbert L. Jones of the Oklahoma A and M College had held to the belief that the electromagnetic radiation from tornadic thunderstorm cells was entirely different from that originating from ordinary non-destructive thunderstorms

and in this connection had begun research in providing proof of his belief. It was by good fortune that during the actual existence of a tornado that data which verified the belief of Dr. Jones was obtained early in this investigation. The equipment used to obtain this data was elementary in nature, and it was desirable that more elaborate devices be employed in an attempt to track the severe storm by means of their characteristic differences.

The early equipment functioned to perceive the high-frequency characteristic of the tornadic-prone cell and distinguish it from other rather harmless cells. The early equipment could detect the presence of a severe storm, but could not establish its location. A contract with the U. S. Signal Corps helped obtain material vitally needed to continue this research program.

The information concerning the times that tornadic activity would be probable was available to Dr. Jones from the Severe Weather Warning Center, at Tinker Air Force Base, which was under the guidance of Col. Fawbush and Major Miller. Using radar and direction detection equipment in conjunction with the original Tornado Laboratory equipment, men working on the project were able to establish facts about the electromagnetic radiations peculiar to severe storms. The early warning from the Severe Weather Warning Center permitted the Tornado Laboratory to begin observations as soon as the storm system was in range and to continue the recording of data until the storm had subsided or had moved out of range to the east.

It was upon this data that new equipment, which determines the severity of a thunderstorm by recording the number of electromagnetic radiations emanating per unit time evolved. Utilizing this new

equipment in conjunction with sequential radar observations, it became possible to forecast the direction of an advancing severe storm center. The tracking of tornadoes and severe thunderstorms had become a reality!

The Air Force established a network of tracking stations, which now utilized a triangulation method of locating storm centers. This network has been associated with the Tornado Laboratory on a voluntary, mutual aid basis since its inception.

The mutual exchange of data has greatly furthered the progress of the storm tracking art. The continued progress of the research program may soon result in a reliable warning system. The techniques are at hand; they must be fully utilized.

#### CHRONOLOGICAL RESUME OF TORNADO RESEARCH SINCE 1952

In January of 1952, a project whose objective<sup>4</sup> was "to study the Sferics originating from the vicinity of tornadic activity" was begun. This project, under the sponsorship of the United States Signal Corps' Meteorological Branch at Fort Monmouth, New Jersey, has evolved an electronic system whereby the path and the severity of a thunderstorm can be determined with surprising accuracy.

In this portion of the introductory chapter is presented a brief history of the milestones that led the way to the present stage of the severe storm tracking art, in order to provide a better understanding of the basic problems encountered to researchers to come.

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<sup>4</sup>Herbert L. Jones, Progress Report No. 1, RESEARCH ON TORNADO IDENTIFICATION, Signal Corps Research Contract No. DA 36-039, File No. 11587-PH-52-91, Dept. of Army Project No. 3-99-07-022, Signal Corps Project No. 172B-0 (Oklahoma A and M College, April 15, 1952), Title Page.



Although sponsored research on this project began only in January, 1952, prior to this date much work had been done to establish a Tornado Laboratory.

In the spring of 1952, the project had three main devices for storm observation: an AN/APQ-13A radar set, an AN/GRD-1A static direction finder, and a relay-operated waveform recorder.

The AN/APQ-13A is a 3 cm wavelength-40KW peak power radar, which exhibits a circular map-like presentation of the thunderstorms and squall lines within a 120 nautical mile radius of the laboratory. On the map-like presentation, called a PPI scan, are also 10-mile range markers so that the radial distance to a given precipitation echo can be accurately determined. The direction can be read by manually adjusting a hairline to coincide with the echo and noting the azimuth indicated on the scale beneath the hairline.

The AN/GRD-1A is an instantaneous sferic direction finder. Although the technical manuals refer to the device as a static direction finder, it is more commonly called a "sferic" direction finder. Sferic, used to describe any electrical disturbance in the atmosphere, is a condensation of the word atmospheric. The purpose of the direction finder is to display on a cathode-ray tube an instantaneous indication of the arrival angles of the electromagnetic radiation from thunderstorms. The presentation is a line extending from the center of the cathode-ray tube (the rest position of the electron beam) radially in a direction corresponding to the correct angle of sferic arrival.

The relay-operated sferic waveform recorder consists of a remotely-located whip antenna, whose output is coupled by electronic amplifiers and is presented on a cathode-ray tube as a function of time. A

relay-type-photographic-synchronizing unit utilizes the whip antenna's signal to photographically record the oscilloscope's presentation.

#### First Year, 1952

The AN/APQ-13A Van-type radar was installed and necessary modifications were made to improve its value in tracking thunderstorms. This included: changed antenna beam-width ( $30^\circ \times 30^\circ$ ), increased duration of peak power output, increased area represented by the PPI scope presentation, construction of a remote control station, and construction of an automatic camera-control unit to automatically record the PPI scope presentation at pre-determined time intervals. A state map was covered with a sheet of plastic, placed on a plotting table, and used to manually record the sequential plots of the storm position.

The AN/GRD-1A sferic direction finder was installed. The Signal Corps sent William G. Stone to check the installation and to install a timing deck, which accurately provided time markers in synchronism with the Bureau of Standards' Station, WWV.

During the first year modifications were made on the existing equipment, or in certain cases new units were designed and constructed to allow the data recording to operate to its maximum capacity. The relay-operated sferic waveform recorder was analyzed and modifications were made to improve its performance. The relay-type photographic-synchronizing unit could operate at a maximum rate of approximately three times per second.

A stroke-repetition rate counter called a strep-rate meter was designed and constructed to count the number of strokes from a given direction by using a photo cell to observe the presentation on the

AN/GRD-1A direction finder. Learning that the Signal Corps had developed and tested a similar device which could be available for the following tornado season, researchers at the laboratory decided to use the Signal Corps' model for it had already been tried and proved under actual storm conditions by the Evans Signal Laboratories at Fort Monmouth. In addition, it had an elaborate scanning device and provided a paper tape record showing the storm intensity as a function of azimuth.

Design and construction was begun on a dual oscilloscope unit called the waveform analyzer. One cathode-ray tube presented the spheric waveform and the other cathode-ray tube presented the direction of spheric arrival from the AN/GRD-1A. Also presented on the front panel were 1 second, 1/10 second, the date, time, and sweep-speed markings. All this data was recorded on a 35 mm continuous motion (no shutter) camera. Thus, when the film was analyzed, all pertinent information was present.

#### Second Year, 1953

Construction was continued on the dual-scope waveform analyzer, which was installed in February, 1953, utilizing the existing relay-type photographic synchronizer.

In the spring of 1953 an all-electronic photographic synchronizer that increased the maximum rate at which spheric waveforms could be recorded to sixty-eight per second was designed and constructed. A video, vertical deflection amplifier for the spheric waveform was installed to increase the detail with which a spheric waveform could be presented. The video amplifier was provided with a filter section to reduce sixty-cycle and broadcast station interference. An integral

part of the photographic synchronizer is a driven-sweep generator (time base), which was designed to be switched to any one of six pre-determined, precise speeds without any additional oscilloscope adjustments. The sweep speed is automatically indicated in coded-form every second on the film. This unit allows sferic waveforms to be analyzed for different durations immediately following the initial lightning discharge.

John D. Hixon from Evans Laboratory visited the project and installed the Signal Corps' stroke counter, called a sferics incidence azimuth integrator.

A simple electro-mechanical timer was designed and constructed to automatically control the radar and waveform analyzer cameras. This device insured an integrated, accumulated supply of storm data. Both radar and waveform analyzer recordings are made every five minutes automatically.

#### Third Year, 1954

A 220 volt, 3-phase, 60 cycle-to-28-volts-200 amp. D. C. rectifier was installed to operate as the standard power source for the radar unit. The standard gasoline-driven 28 volt D. C. generator is maintained for auxiliary radar power. A manually operated switch-over device was provided so that in case of regular power failure the gasoline-driven unit could be quickly employed. A 7.2 KW gasoline-driven 60-cycle auxiliary power plant is available to operate the other laboratory equipment in case of regular power failure.

A new high-frequency sferic direction finder (HFDF) was designed and constructed by the author of this paper. The normal tuning

procedure for the standard AN/GRD-1A (the Signal Corps low-frequency direction finder) requires considerable technical ability for proper results, but this new HFDF unit employs a pulse tuning technique, which can easily be performed perfectly by non-technical personnel.

The early results of the new direction finder are so promising that it may become the standard direction finder for severe thunderstorms. When the AN/GRD-1A direction finder fails because of ellipsing on severe storms, the new high frequency direction finder continues to function and actually shows that one lightning stroke is composed of several discharges along the same ionized path.

The dual-scope waveform analyzer was modified so that it uses a fast writing rate, cathode-ray tube, type 5RP11, which requires a 15,000 volt accelerating potential. This new tube provides for proper photographic recording of the new high frequency direction finder. Two new video deflection amplifiers, however, were required to give adequate deflection voltages for the 5RP11 tube.

A servo-motor-driven pen mechanism was designed and constructed to record the output of the Signal Corps' stroke counter, because the General Electric recording milliammeter did not have sufficient power to overcome friction between the pen and the paper tape. An accurate, low-frequency (1 to 30 cps) pulse generator was used to calibrate the counter. Formerly the pulse generator had been devised to calibrate the author's strep-rate meter.

#### Fourth Year, 1955

A new switching device was designed to automatically switch the dual-oscilloscope waveform analyzer into either one of two recording combinations: a recording of the Standard Signal Corps AN/GRD-1A

direction finder and the high-frequency direction finder simultaneously, or the AN/GRD-1A direction finder and sferic waveform simultaneously.

During the spring of 1955, the AN/GRD-1A was modified to help reduce some of its ellipsing tendencies. The result, however, also reduced the light output to such an extent that the Signal Corps sferic counter would not function. The receiver unit was then sent to Fort Monmouth for additional modifications.

In the summer of 1955, a counter that exhibits high angular resolution and functions automatically was designed and constructed to work in conjunction with the new high frequency direction finder.

The output of the counter is recorded on a moving paper tape and exhibits a plot of storm intensity as a function of azimuth. The azimuth scale is automatically coded on the paper tape at  $10^{\circ}$  intervals.

Plans were made to patent the author's high frequency direction finder, but financially it could not be justified by the Division of Engineering Research.

A surplus oscilloscope was modified to enable it to exhibit the high frequency direction finder presentation; and a manually operated azimuth scale was fitted to the face of the cathode-ray tube. In as much as the sferics from a given severe thunderstorm are presented on the high frequency direction finder as an almost continuous display at the appropriate angle, the hairline can be rotated to coincide with this display and the active angle can be read accurately. This device is referred to as the "Visual HFDF Unit."

A  $90^{\circ}$  azimuth rotation device was designed and constructed to alter the HFDF presentation on the dual scope unit. In normal operation the HFDF scope presentation exhibits North to the left and East to the top

of the scope; upon operation of the 90° azimuth rotation device, North is presented at the top and East at the right of the oscilloscope face. With this arrangement, maximum storm activity can be maintained at nearly right angles to the direction of film travel. A neon light is used to code the film when North has been switched to the top of the scope.

An additional pen was added to place information on the paper tape record of the high frequency direction finder counter to indicate the periods when the camera-drive motor for the dual scope unit is in operation. Thus, a record is available to show the operator that data has been taken, and to show the film analyst when simultaneous records of counter and film are available.

In the fall of 1955, design and construction were begun on a so-called "Composite Picture Device." The function of this device is to automatically control all camera operations at various adjustable rates. In addition, it is to take time exposures of the high-frequency and the AN/GRD-1A direction finders for purposes of analysis. These time exposures of various lengths are called "composite pictures" in that all the active sferic angles are presented on one picture.

#### Fifth Year, 1956

Construction was completed on the "Composite Picture Device" and it was installed in February, 1956. A third complete modification was performed on the AN/GRD-1A when it was learned that a newly modified receiver unit belonging to the Air Force would function in our system; our receiver would not function properly under the same conditions. The reduction in ellipsing was considerable. When a new sense receiver

was designed along the principles of the high frequency direction finder, the overall performance of the AN/GRD-1A was good.

The same principles of azimuth orientation that were used on the high frequency direction finder were employed on the AN/GRD-1A in order to bring its presentation into agreement with known storm locations. The resulting presentations of the AN/GRD-1A and high frequency direction finder can now be correlated on storms much closer to the Tornado Laboratory.

Design and preliminary tests were begun on a new multiple-frequency direction finder which will operate on different frequencies within the range of 20 kilocycles to 500 kilocycles per second. This unit will be used to investigate the belief that the energy distribution of the electromagnetic radiation from thunderstorms shifts into higher frequency bands as the storm becomes more severe.

A new waveform filter was designed and constructed to help reduce the interference from radio station KRMG. The filter is incorporated in the pre-amplifier stage, coupling the waveform cathode follower to the vertical deflection amplifier.

A new camera, named the Optical Stroke Recorder, was installed to take actual photographs of the lightning stroke. A control device was installed to correlate the operation of the optical recorder with the recordings of direction finder presentations on the dual-scope waveform analyzer. The period of operation, timing markers, record number, and the azimuth of the Optical Stroke Recorder are coded on the film of the dual-scope waveform analyzer.

Tests were made with a Van de Graaff generator to calibrate the reception pattern of the AN/GRD-1A, but the results were negative.



### 1956 Operating Procedure

The semi-block diagram shown in Figure 1 illustrates the overall equipment arrangement used for tracking storms during the 1956 season. It was learned during the 1955 season that visual observation of the high frequency direction finder (HFDF) could be used to estimate the angles of most intense activity and that by extending lines at these intense angles until an intersection with the precipitation echoes shown by the radar was obtained, a location of the most intense storm areas could be determined with surprising accuracy. Early in the 1955 season a project was begun whereby this data could be determined with better than estimation accuracy. In addition, a scanner was constructed to use in conjunction with the electronic counter built in 1952. This unit is used to obtain the relative intensities of the various storms by measuring the relative stroke repetition rates.

As can be seen in Figure 1, the operator, who is located at the plotting table, has at his disposal the visual radar scope, the visual HFDF scope, and the HFDF counter output from the paper tape. The entire system can be controlled by one operator checking on distant storms or even on near-by storms of low intensity; but, when the storm is near-by and severe, three operators can be used to advantage.

In order to present an integrated picture of how the system functions, the purpose of each part of the system will be discussed individually, telling how each bit of data is recorded, and how it is utilized by the operators in determining the instantaneous condition and location of the storm.

First of all, in the upper left hand portion of the drawing is depicted the 10 kilocycle AN/GRD-1A spheric direction finder. This

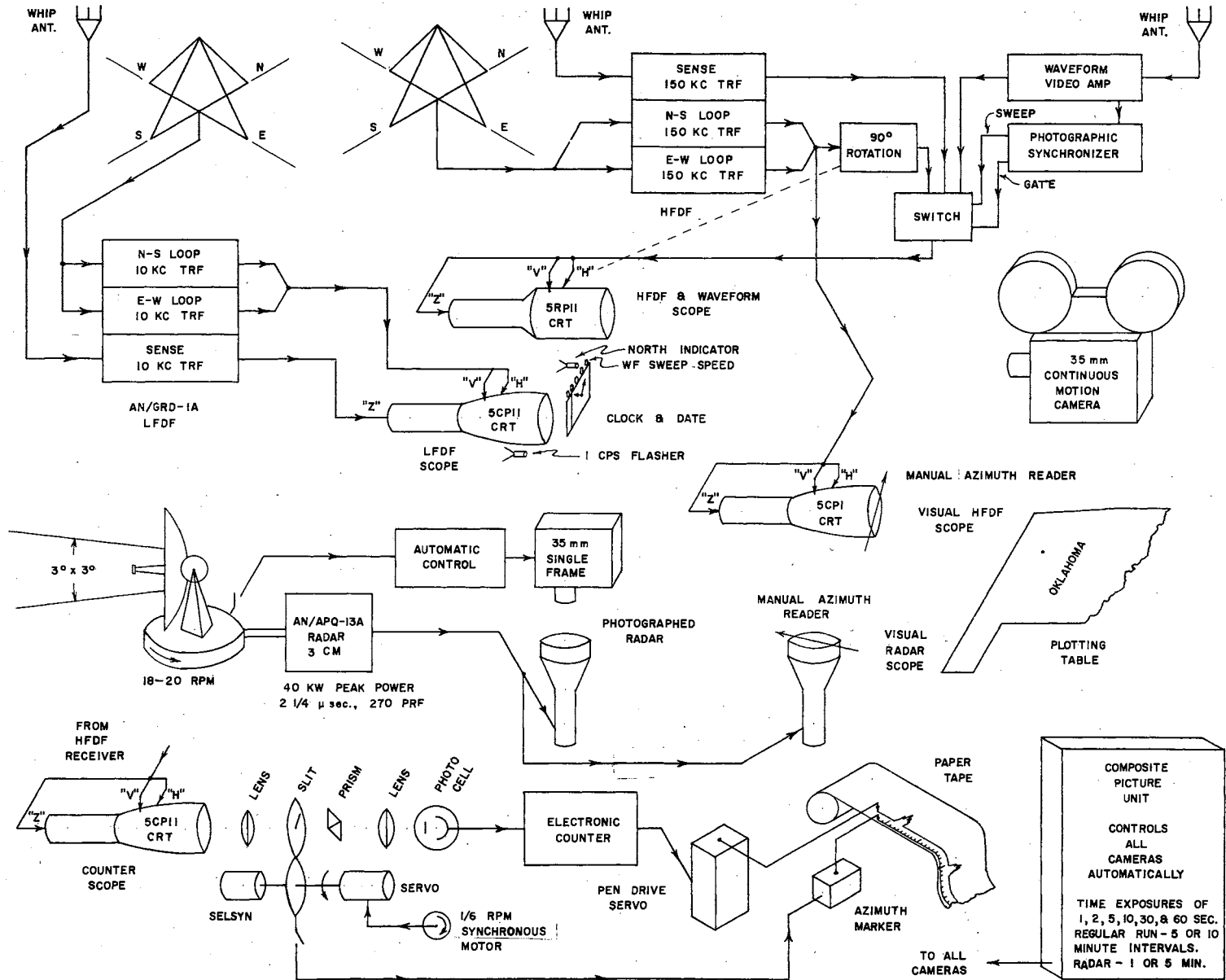


Figure 1. Semi-block diagram of the equipment used during the 1956 tornado season.

unit consists of two single-turn, coaxial-loop antennas orientated in the North-South and the East-West directions, respectively. The output from this loop antenna system is fed to two identical, tuned-radio-frequency (10KC TRF) receivers. The output of the two receivers is presented on the 5CP11 cathode-ray tube (CRT). A vertical whip antenna feeds a sense receiver, whose output controls the electron gun of the CRT. The presentation is a line of light extending radially from the center of the CRT, whose direction corresponds to the sferic generating storm. This CRT presentation is photographically recorded at regular intervals of 5 minutes by the 35 mm continuous motion camera. At the present time, this presentation is used for comparison with a similar presentation on the high frequency direction finder (HFDF, 150 kilocycles).

The block diagram representing the HFDF is in the top center of the drawing. A similar antenna system is used to feed the 150 KC TRF receivers. The 5RP11 CRT is used to present the HFDF picture; but this CRT serves a dual purpose, which accounts for the switching device connected between the direction finder's output and the input to the CRT. A 90° azimuth rotation device at the output of the two loop amplifiers is required in order to maintain presentation of the maximum activity at nearly right angles to the direction of film travel. This device has two positions: one position places the North-direction at the left on the scope face and the other position places North at the top of the scope face.

The 5RP11 CRT has a second mode of operation whereby it presents the sferic waveform. The vertical whip antenna, which feeds the waveform video amplifier, is shown in the upper right-hand portion of Figure 1. 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 spheric waveforms and generates a time base and an electron-gun gating pulse for presenting this waveform on the 5RP11 CRT when it is in the waveform mode of operation. The 10-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, it is seen from the foregoing discussion that the camera records simultaneously the HFDF and the AN/GRD-1A, or waveform and the AN/GRD-1A. Time, date, sweep speed, and HFDF North indicator recordings appear on the film record at 1 second intervals. Regular run recordings are made every five minutes for 0-60 seconds in length. The camera is controlled by the composite picture unit, which is shown in the lower right corner of the drawing. The composite picture unit also utilizes the camera to take various length time exposures of both scopes in the direction finding mode of operation.

The output of the HFDF receiver is taken just ahead of the 90° azimuth rotation device and used to obtain an HFDF scope presentation for visual observation by the operator. The visual HFDF scope is provided with a manually-controlled, azimuth hairline, with the result that active angles can be read to about a 2° accuracy.

The output of the HFDF receiver is also used to obtain an HFDF scope presentation for counting purposes (lower left hand of drawing). The counter scope's presentation is focused by means of a lens at the plane of a revolving slit that rotates 10°/ second. This scanning method eliminates parallax problems caused by the thickness of the glass at the scope's face. The light output from the slit is fed by a prism

and lens arrangement to a photoelectric cell.

Whenever light reaches the photocell, it is an indication that spheric activity is occurring at the particular angular location of the slit. The resultant light impulses, representing spheric activity, produce by means of the electronic counter a voltage which is proportional to the repetition rate of the spherics. This voltage causes the pen-drive servo to record a corresponding indication on the paper tape.

A small electrical switch is operated by the rotating slit every  $10^{\circ}$ , and this causes an azimuth mark to be recorded along with the spheric count on the paper tape. Every  $90^{\circ}$  impulse from the azimuth marker is of greater amplitude, and the one representing  $0^{\circ}$  is followed by an additional mark at  $4^{\circ}$ , in order that the four cardinal points may be easily recognized. Because a synchronous motor is used to control the slit-drive servo, no check need be made to record the times associated with the paper tape recording 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 paper tape's recording 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: an 0-10 pulses per second scale, and an 0-30 pulses per second scale.

The radar employed is an AN/APQ-13A, modified for weather observations. It has a wavelength of 3 cm, a peak power of 40 KW, a pulse duration of  $2 \frac{1}{4}$  microseconds, a pulse recurrence frequency of 270 p.p.s., an antenna speed of 18-20 r.p.m., and a  $3^{\circ}$  beam width. The radar scope presentation at the operating console is photographed automatically every 1 or 5 minutes by a 35 mm single-frame, relay-operated camera. 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 hair-line. Thus, the precipitation echoes shown by the radar can be plotted on the plastic sheet covering the state map. These plots are made every 5 or 15 minutes as determined by the velocity and activity of the storms. The time of each plot is recorded on the plastic sheet which is saved to be used on an identical map for future analysis.

Within radar range, the most intense storm areas 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.

Now that the individual parts of the system have been discussed, a resume will help give an integrated picture of the system. Since advance warnings are always available from the Severe Weather Warning Center in Kansas City, the operator has ample time to put the system in operation by aligning all the direction finding equipment, synchronizing all clocks and synchronously driven units with the Bureau of Standards, WWV, placing date cards in photographed units, and testing all camera equipment. Once the system has been properly adjusted for operation, it is only necessary to check occasionally to be sure that all scopes are in proper agreement.

The operator records the location of all precipitation echoes shown by the radar on the state map of Oklahoma. He then reads and records the active angles, as shown by the visual presentation of the high frequency direction finder, noting in particular those angles

that appear most active. Next, a reading of the HFDF counter record from the paper tape is made and recorded adjacent to the visual HFDF record. These records are then checked for agreement. The maximum stroke counts as indicated on the counter record are carefully compared with the visual intensity observation.

Next an intersection is made of the most intense activity angles with the radar plot on the state map. These areas of intersection are carefully noted on the plotting table map. This same procedure is repeated 15 minutes later and the directional movement of the most active areas is noted. The radar alone does not indicate the exact path of the severe areas. They frequently move along the length of the cloud configuration that is presented by the radar and give no indication of the sliding of the active portion along the configuration.

Information obtained is forwarded to the Severe Weather Warning Center in Kansas City, whose information comes from observers, their AN/GRD network, and meteorological data. This data is used to confirm the accuracy of storm intensity indications derived at the Tornado Laboratory.

Increasing count trends on the HFDF counter have been obtained and subsequently followed by observer reports of hail and severe winds, or tornadic activity in the area so indicated by the equipment. Results so far are quite promising. As more data is acquired of storms tracked and correlated with observations made at the centers, an index can be drawn, making it possible to predict exactly the severity of the storm from the equipment indications.

## CHAPTER II

### AN ALL-ELECTRONIC SPHERIC WAVEFORM RECORDER

The requirements of a spheric waveform recorder that utilizes a continuous motion recording camera are as follows:

1. The associated high-impedance whip antenna should be located out of the region of man-made interference.
2. The amplifiers at the antenna should be completely supplied by direct current in order to reduce power-frequency interference.
3. The electromagnetic energy of the spherics should be received by a device with as little frequency distortion as possible.
4. The voltage representing the received spheric should be transmitted from the remote antenna to the recording equipment with a minimum amount of attenuation.
5. The voltage wave arriving at the recording equipment should be amplified and presented on an oscilloscope; the amplifiers should contain filters to eliminate undesired signals from radio stations and from 60-cycle power system sources.
6. Spheric waves below a given amplitude should be rejected.
7. The spheric wave selected should trigger the oscilloscope sweep and turn on the cathode-ray tube's electron



7. beam.
8. Sferic waveforms that follow immediately should not trigger another sweep until the film has advanced sufficiently to prevent overlapping of records.
9. When the film has sufficiently advanced, the equipment should be ready for the next incoming sferic wave.
10. Some means should be provided for correlation between the exhibited waveforms and the direction of sferic arrival.

When the redesigning of the waveform recorder took place in order to make the system completely electronic, the first four of the preceding requirements were satisfied by a cathode follower unit, which adequately matched the vertical whip antenna to the long 50-ohm coaxial cable of the Tornado Laboratory.

#### Antenna Cathode Follower

The schematic of the antenna cathode follower unit and its associated power supplies is shown in Figure 2.

The cathode follower unit should be located away from the other equipment in the Laboratory in order to reduce the interference from the power lines. The regulated low-voltage d. c. plate power supply and the regulated d. c. filament supply are additional refinements to help reduce the interference from the 60-cycle power source. These features reduce considerably the power frequency interference; however, the fields associated with the 3  $\phi$  power source still slightly affect the waveform application, even though the antenna cathode follower unit is located nearly 70 yards from the building. The filament and plate supply voltages as well as the returning sferic signal are coupled by

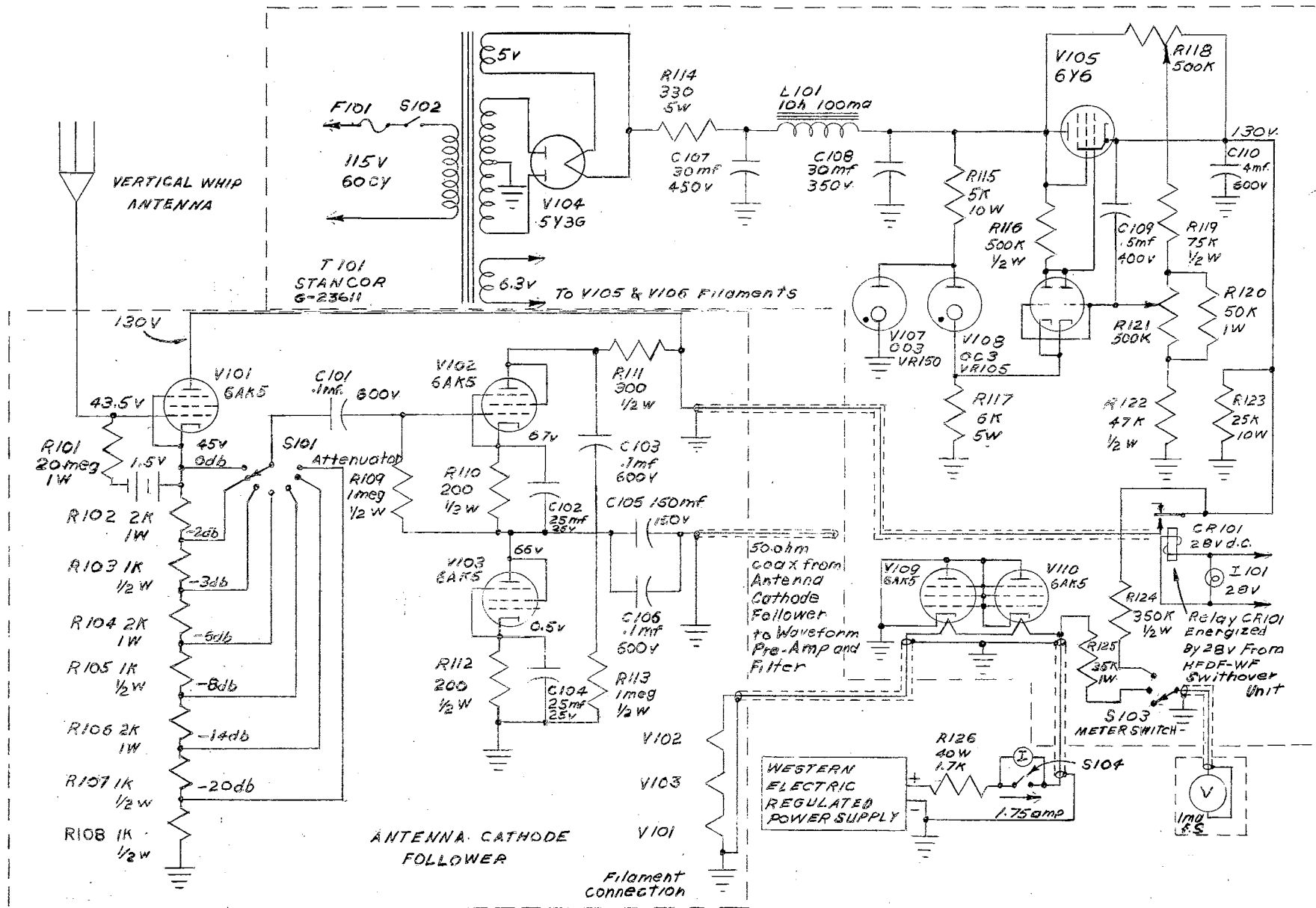


Figure 2. Circuit diagram of the Antenna Cathode Follower and associated power supplies.

means of coaxial cables extending from the Laboratory to the cathode follower unit.

The unit functions to provide a proper match between the high-impedance whip antenna and the low-impedance coaxial cable, which couples the spheric signal to the waveform pre-amplifier and filter unit.

The design considerations for a cathode follower with a high input impedance, a high gain approaching unity, and a low resistance load are conflicting<sup>1</sup>, especially if a relatively large input signal must be tolerated. However, if the signal level is low and use is made of a double cathode follower arrangement, the first four of the above requirements can be adequately satisfied.

Tube V101 is connected as a conventional cathode follower except that the grid is returned to the cathode and fixed bias is employed. When a signal appears at the grid, the potential of the top of resistor R101 varies according to the input signal, but the potential of the bottom of R101 varies according to the output signal on the cathode. If the gain of the cathode follower stage is near unity, a small voltage appears across the resistor R101. Consequently, a small signal current can be drawn from the source of the grid signal.

This principle of operation causes the resistor R101 to appear to be many times larger than its actual ohmic size. This property also gives the input cathode follower the required high input impedance necessary to properly terminate the high-impedance whip antenna. As the impedance of the load is decreased, the gain of a cathode follower is consequently reduced.

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<sup>1</sup>Herbert J. Reich, Theory and Application of Electron Tubes (2d ed., New York and London, 1944), p. 174.

In the first stage of the antenna cathode follower unit, any appreciable load which reduces the gain of tube V101, necessarily decreases the high input impedance. Therefore, as little load current as possible should be required from the first stage. This requirement is accomplished by feeding the first cathode output into a second cathode follower circuit.

The second cathode follower circuit<sup>2</sup> of low output impedance consists of tubes V102 and V103 and the associated components. The purpose of this cathode follower is to provide an extremely light load for the first cathode follower V101 and yet provide a low output impedance to drive the 50 ohm coaxial cable feeding the waveform pre-amplifier and filter unit.

A step-gain control is provided at the cathode of tube V101 in order that the amplitude of the signal which is fed to the second cathode follower can be adjusted to correspond to the distance to the storm. Whenever the storm approaches, the gain must be reduced to prevent over-driving the second cathode follower. The average amplitude sferic should be presented on the oscilloscope with a peak-to-peak deflection of about two inches.

Measurements indicate that the overall gain from the antenna to the output of the coaxial cable is 0.2. This is approximately 100 times larger than the original single cathode follower system. The overall frequency response of the system is greatly increased, especially on the low frequency end.

The filaments and the plates of the antenna cathode follower unit were originally supplied by batteries located inside the housing for the unit.

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<sup>2</sup>Calvin M. Hammack, "Cathode Follower of Very Low Output Resistance," Electronics (November, 1946), p. 206.

However, frequent battery trouble made the use of electronic power supplies more desirable. The power supply for the plate circuit, whose schematic is shown in Figure 2, is conventional in all respects except for the feedback and reference voltage arrangement. This particular circuit arrangement was devised by the author for a group of regulated power supplies constructed for classroom use. In the feedback circuit, a portion of the input to the regulator circuit as well as a portion of the output voltage is coupled back to control the series regulator tube V105 (6Y6). The output voltage can be adjusted to give zero per cent regulation from no load to full load by selection of proper settings for resistors R118 and R121. The effects of the two adjustments are mutually dependent. Nevertheless, a proper setting of each resistor can be found to provide a constant output voltage as the load current is varied from zero to the full load value. In this particular application, the output voltage was adjusted to be constant at 130 volts throughout the range of load current from zero to 30 milliamperes. The antenna cathode follower requires approximately 15 milliamperes at this voltage.

In order that a regulator circuit of this type can operate at this low an output voltage, a stable low value of reference voltage is needed for the amplifier tube V106 (6SL7). This reference voltage is obtained by the unique connection of the glow-type voltage regulator tubes V107 and V108. Tube V107 tends to maintain 150 volts across its terminals, but tube V108 tends to maintain only 105 volts across its terminals. Under these conditions, the voltage appearing across resistor R117 tends to remain constant at 45 volts, the voltage difference of the two tubes. This lower value of voltage is returned to the cathode of tube V106 to serve as reference voltage with which to compare the feedback voltage

from resistor R121.

Two features are employed to help reduce any ripple frequencies at the output terminals of the plate power supply. These are the addition of the condensers C109 and C110. Condenser 109 provides increased negative feedback at the ripple frequencies, and condenser C110 provides a low impedance shunt to ground for the ripple frequencies at the output terminals.

A Western Electric regulated power supply is used as the d. c. filament power source. The first modifications to eliminate the use of batteries called for a 30 volt d. c. Western Electric Telephone battery eliminator. However, the tungar-type rectifier tubes in the apparatus created an undesirable interference in the waveform receiver. This original connection required five 6AK5 tubes to be in series across the telephone battery eliminator. This original modification accounts for the two 6AK5 tubes (V109 and V110) inside the plate power supply cabinet. When the Western Electric regulated power supply was installed, a 1700 ohm series resistor was the only additional modification to properly satisfy the filament requirements. The output of the regulated power supply is adjusted to give the necessary 175 milliamperes of filament current. A meter can be connected in series with the filament circuit to aid in properly setting this current.

A voltmeter circuit is provided to check the filament and plate supply voltages. The voltmeter circuit is also handy to indicate an open filament in the 6AK5 tubes. The indication for an open filament in any of the 6AK5 tubes is an abnormally high reading on the meter when set to read filament voltage. The series multiplying resistors

R124 and R125 have been selected to cause a meter indication of approximately half-scale under normal conditions.

It should be noted that in order for the antenna cathode follower to function, relay CR101 must be energized. This relay is energized by the 28-volt radar power source whenever the system is put into the waveform mode of operation. The connections for applying 28 volts to relay CR101 are controlled by the WF-HFDF switchover device which was mentioned in Chapter I. Because many signal voltages are terminated in the WF-HFDF switchover device, it was considered advisable to prevent the high-amplitude, waveform sweep voltages from reaching there. This result is accomplished by removal of the plate voltage from the antenna cathode follower whenever relay CR101 is de-energized, and this, in turn, prevents a sweep from being generated when not in waveform operation.

Upon selection of the waveform mode of operation, relay CR101 is energized and plate voltage is applied to the antenna cathode follower. Electrical signals, received by the whip antenna are coupled by the antenna cathode follower to the 50-ohm coaxial cable, which is terminated at the input to the waveform pre-amplifier and filter unit.

#### Waveform Pre-Amplifier and Filter Unit

The schematic for the waveform pre-amplifier and filter unit is shown in Figure 3 along with the schematic of the vertical deflection amplifier. The coaxial cable extending from the remote antenna cathode follower unit is terminated by resistor R127 in the grid of tube V111. Thus, the signal appearing at the grid of tube V111 is a time varying

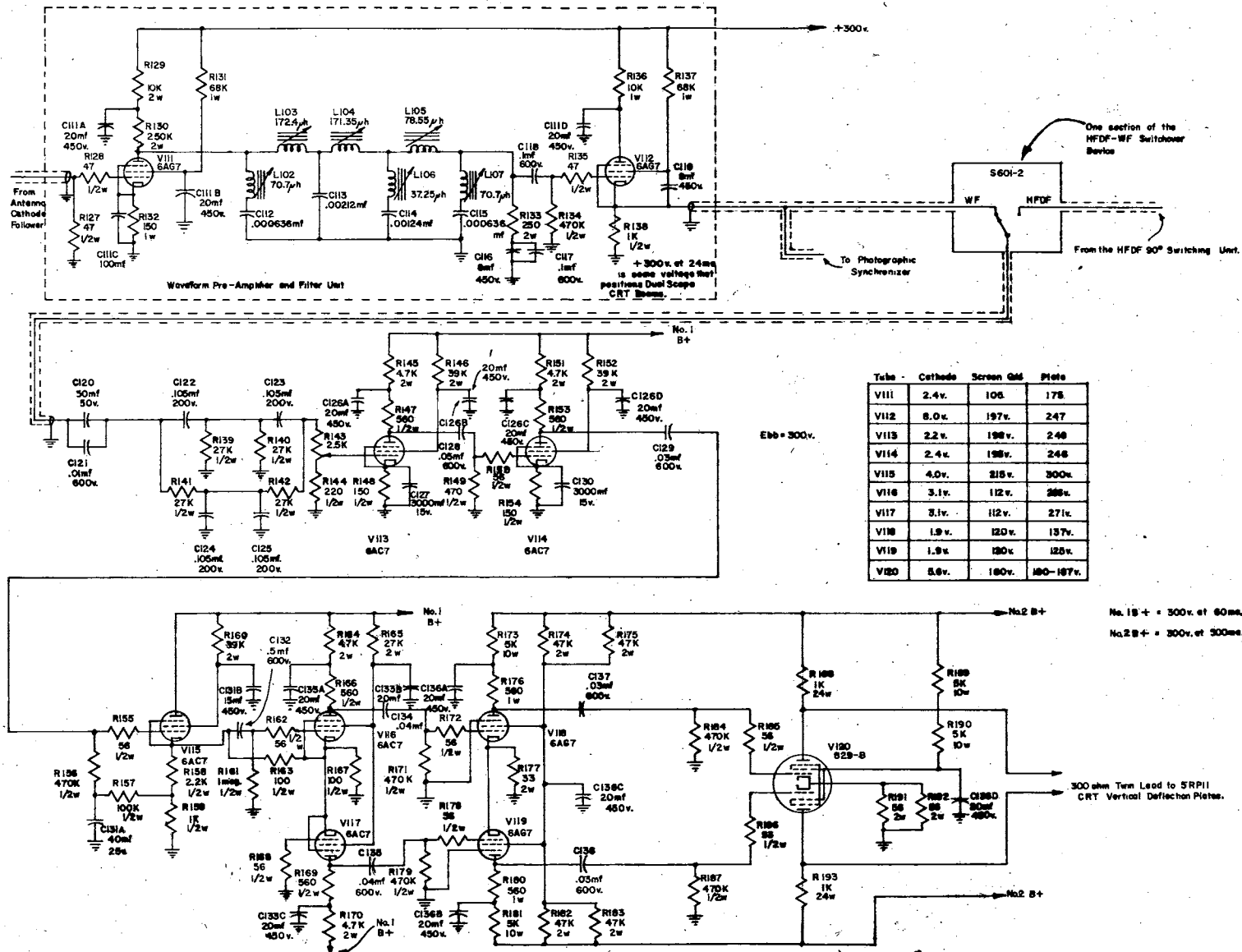


Figure 3. Circuit diagram of the Vertical Deflection Amplifier for the 5RP11 cathode-ray tube and of Waveform Pre-Amplifier and Filter Unit.



voltage representing the radiation from thunderstorm activity.

Broadcast radio station interference as well as sixty-cycle power line interference is also present in this signal. It is the purpose of this unit to amplify the waveform signal and also to reduce or reject the undesirable interference signals from broadcast radio stations. An additional filter is employed in the deflection amplifier to reduce sixty-cycle power line interference.

An m-derived low pass filter<sup>3</sup> was designed to have a cutoff frequency of 600 kilocycles and to give as much attenuation as possible to the frequency of most interference, 740 KC from radio station KRMG in Tulsa. A characteristic impedance of 250 ohms was chosen, for this value gave inductance requirements which were easily satisfied with available components. Shields for the inductors were constructed from old metal tube shells, and the value of each inductor was set to the desired magnitude, using a General Radio type 650-A impedance bridge for measurements. The GR bridge was also used to select a group of capacitors, the sum of which gave the desired value of capacitance when the group was connected in parallel. The complete filter consists of inductors L102, L103, L104, L105, L106, and L107, in addition to the condensers C112, C113, C114, and C115 as shown in Figure 3.

Tube V111 is connected to drive the filter with an output impedance of 250 ohms as provided by its plate load resistor R130. The filter is terminated by a 250-ohm resistor, R133. In order to prevent the d. c. voltage on the plate of tube V111 from being shorted

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<sup>3</sup>William L. Everitt, Communication Engineering (2d ed., New York and London, 1937), pp. 197-210.

to ground by the terminating resistor R133, the lower end of the resistor is returned to ground through the parallel combination of C116 and C117. Although the two condensers provide an excellent ground for useful signal frequencies, they present an open circuit to the d. c. potential from the plate of V111.

The signal appearing at the grid of tube V112 from the output of the filter is a time-varying voltage, representing the spheric waveform almost completely void of any broadcast station interference. Tube V112 is connected as a cathode follower to feed this signal voltage on to the vertical deflection amplifier and to the waveform photographic synchronizer. In Figure 3 it can be seen that the output of the waveform pre-amplifier and filter unit is coupled to the vertical deflection amplifier by means of one section of the WF-HFDF switch-over unit.

A twin-T filter<sup>4</sup>, which is designed to eliminate a frequency of 60 cycles per second, is located at the input of the vertical deflection amplifier. The circuit for the amplifier is a modified version of one used in the Western Electric D-25641 oscilloscope and is quite conventional in every respect. Tubes V113 and V114 are conventional resistance-capacitance-coupled, video amplifiers. Tube V115 is a cathode follower used to drive the phase splitter circuit, which consists of tubes V116 and V117. Tubes V118 and V119 are push-pull driver tubes for the push-pull final stage V120. The output of the amplifier is coupled by 300-ohm twin lead to the vertical deflection plates of the 5RP11 cathode-ray tube.

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<sup>4</sup>Samuel Seely, Electronic Engineering (1st ed., New York, Toronto, London, 1956), p. 239.

The power supply requirements for the deflection amplifier are critical in that two power supplies are required to prevent a motor-boating condition. The first power supply of 300 volts supplies all tubes except the drivers V118 and V119 and the final V120 and delivers a current of approximately 65 milliamperes. The last three tubes are supplied by a regulated power supply of 300 volt-500 milliampere capacity, which delivers approximately 300 milliamperes.

As stated in a previous paragraph, the output of the pre-amplifier and filter unit is also fed by a coaxial cable to the electronic photographic synchronizer. The electronic photographic synchronizer, whose schematic is shown in Figure 4, must perform the function of selecting the sferic waveform to be presented and also generate a trigger pulse to initiate the sweep generator in order to present the waveform on the cathode-ray tube.

The reason why some type of selection process must be employed becomes obvious when the number of sferics that arrive each second are compared to the rate of film travel in the camera. In a one-second interval, a single severe thundercell may produce as many as thirty discharges. Although there are many thundercells in a given storm system, the total number of sferics arriving from all directions can be several times greater.

A continuous record of the voltage induced in the waveform antenna is desirable. However, the required pre-requisite is a film travel of several feet per second. The present normal rate is 2 inches per second. The waveform is presented on a time base that is normal to the direction of film travel and the waveform amplitude variations in the direction of film travel. It is desirable that successive waveform

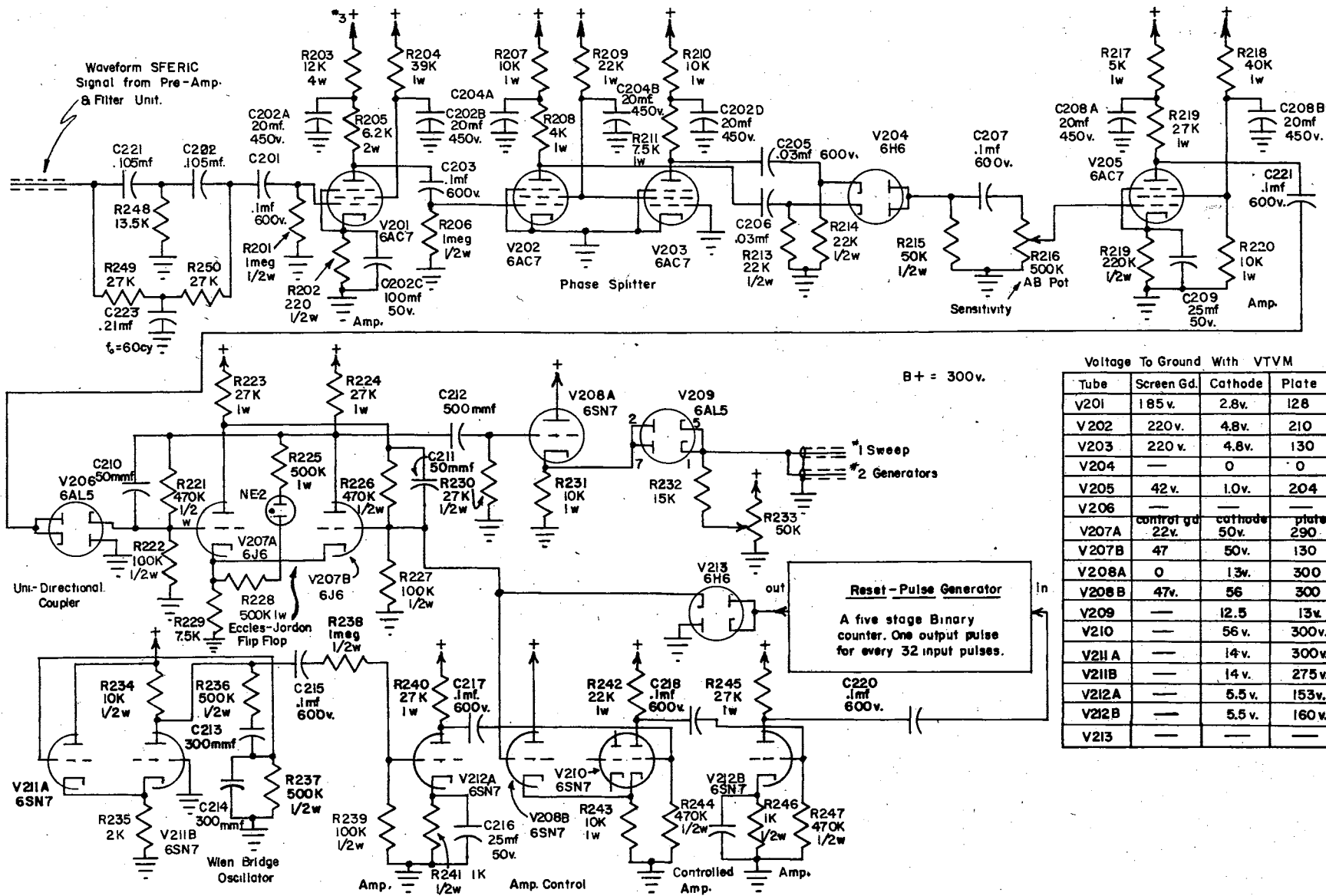


Figure 4. Circuit diagram of the Electronic Photographic Synchronizer.

records do not overlap excessively. The method of selecting the particular wave to be exhibited is by amplitude discrimination; the amplitude of the waveform must exceed the prescribed sensitivity level in order to trigger a sweep and present itself. The method of preventing excessive overlapping of recordings is to control the delay in resetting the selector circuit in preparation for presenting the next recording. Since the original relay-type photographic synchronizer did not have a precise delay circuit, it was subject to multiple and overlapping records.

The electronic method for satisfying the conditions described above and as prescribed by requirements 6 through 9 in the list given at the outset of this chapter is described in the following circuit descriptions. As indicated in Figure 4, the signal representing the sferic waveform is coupled into the grid of tube V201 from the waveform pre-amplifier and filter unit. Tube V201 is connected as a conventional wide-band pentode amplifier to further increase the magnitude of the sferic signal. Tubes V202 and V203 are connected to form a cathode-coupled phase splitter for producing both positive and negative polarity signals, representing the sferic waveform.

The output of the phase-splitter circuit is fed to a full-wave diode detector, tube V204. Tube V204 functions to provide a negative sferic across resistor R215 in its plate circuit regardless of the polarity of the initial sferic discharge. The negative sferic signal appearing across R215 is coupled by condenser C207 and appears at the sensitivity control R216. A portion of the sferic signal, depending upon the setting of the arm of the sensitivity control, is coupled to the grid of the amplifier tube V205. The primary function of tube V205 is to invert the sferic signal and provide a positive polarity

signal at its output. It does, however, give some amplification to the signal.

Tube V206 is employed as a uni-directional coupling device to feed the sferic signal from the plate of tube V205 into the grid of tube V207A. Tube V207 is connected as a conventional Eccles-Jordan trigger circuit<sup>5</sup>. The Eccles-Jordan trigger circuit, sometimes referred to as a flip-flop multivibrator, has two stable states of operation. In the first state, one of the triode sections conducts, providing voltages which prevent the other triode section from conducting; the other stable state exists when the reverse is true for the respective tubes. The two tube sections can be forced to switch from one stable state to the other by the application of a positive triggering pulse of sufficient amplitude to the grid of the non-conducting tube. If the triggering pulse is not of sufficient amplitude, the switching process does not occur. This amplitude-sensitive property prevents triggering of the circuit on sferics whose amplitude is below the required level.

In the circuit under consideration, the two tubes are housed in a single envelope, and prior to the arrival of a sferic waveform, tube V207B is in the conducting state. Under these conditions, the plate potential of tube V207B is relatively low because of the heavy conduction through the plate load resistor R224. The grid potential of V207B is quite positive, relative to ground, but at approximately the same potential as the cathode. It should be noted that the potential at the grid of tube V207B is coupled directly to the grid of V208B, which makes V208B also conduct heavily. The fact that V208B

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<sup>5</sup>Herbert J. Reich, p. 356.

is conducting heavily because of the potential existing at the grid of V207B is mentioned at this point, for, as will be seen shortly, the current of tube V208B flowing through the cathode resistor R243 controls the operation of the amplifier tube V210. Whenever the grid of tube V208B is relatively positive, its resulting plate current through R243 is sufficient to keep tube V210 from operating.

It should be noted that the above conditions require tube V207A to be in the non-conducting state prior to the arrival of the triggering sferic. When a sferic of sufficient amplitude is received, a positive triggering impulse is applied through tube V206 into the grid circuit of tube V207A. This positive triggering impulse corresponds to the initial part of the sferic discharge. Consequently, the multivibrator circuit immediately switches to the state wherein tube V207A is conducting and tube V207B is non-conducting.

At the very instant this switching action takes place, the grid potential of V207B immediately assumes a much larger positive value. The result of the reduction in grid potential of V207B is the immediate reduction in current through tube V208B, a process which allows amplifier tube V210 to commence operating in a conventional manner. The result of the instantaneous rise in plate potential of V207B is the production of positive impulse at the grid of tube V208A because of the differentiating action of condenser C212 and resistor R230.

The rising plate potential of V207B constitutes the application of a positive step-function of voltage to the short time constant R-C circuit composed of R230 and C212. The voltage resulting across resistor R230 rises instantly to a positive value equal to the change in plate potential of V207B and then dies away to zero exponentially.

However, sferic signals are super-imposed upon this positive "spike" of voltage because of the coupling action of V206, R221 and C210 in the grid circuit of V207A.

In order to obtain a positive spike of voltage, free of any subsequent sferic waveform variations, an amplitude-selector clipping circuit<sup>6</sup> is employed to provide an output only when the potential rises to a value more positive than that existing at the arm of potentiometer R233. The principle of operation is quite simple. The voltage, consisting of the positive spike with super-imposed sferic signals at the output of cathode follower V208A, is applied to the clipper circuit V209. Tube V209 will not conduct unless the potential on its plate exceeds the potential on its cathode as set by the position of the potentiometer arm of R233. A setting of R233 can be found which prevents conduction of tube V209 except for the interval of time represented by the positive exponential pulse. The impulse of current that results from the momentary conduction of tube V209 produces a positive voltage impulse across R232, an impulse which is fed to the sweep generator to initiate the sweep for presentation of the waveform on the cathode-ray tube.

The triggering of multivibrator tube V207 by the sferic signal also allows tube V210 to commence operating as a conventional amplifier. The result of the action, allowing tube V210 to commence operating as a conventional amplifier, can best be described by following the signal that arrives at the grid of tube V210 from its origin.

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<sup>6</sup>Britton Chance et al., Waveforms (New York, Toronto, London, 1949), pp. 365-366.



Tube V211 is connected as a Wien-Bridge oscillator<sup>7</sup> to continuously generate a sine wave, whose frequency is controlled by the values of resistors R236 and R237 and condensers C213 and C214. If the ohmic value of R236 is equal to that of R237 and if the capacitance of C213 is equal to that of C214, the frequency of oscillation in cycles per second is given by

$$f = \frac{1}{2\pi RC}$$

where R is the value of either resistor in ohms and C is the value of either capacitor in farads.

The frequency may be altered by substitution of different values of capacitance or resistance in the frequency-sensitive network. The frequency for the values of components shown is approximately 1000 cycles per second. The output from the oscillator is coupled from the plate of tube V211 B to the grid of tube V212A by C215, R238, and R239. The amplitude of the output from the oscillator is sufficient not to warrant the use of the amplifier tube V212A. A signal from an external source can be injected at the grid of V212A for purposes of testing, but the additional gain of tube V212A is necessary. One such source is the 6.3 volt filament supply. When an external signal is employed, it is advisable to disable the Wien-Bridge oscillator by removing tube V211A from its socket.

Under normal operating conditions, the Wien-Bridge oscillator is employed to feed the grid circuit of tube V212A. Resistors R238 and R239 form a voltage divider to reduce the magnitude of the signal

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<sup>7</sup>Reich, pp. 396-398.

from the oscillator that reaches the grid of tube V212A, preventing excessive over-loading of the amplifier and the oscillator. Tube V212A is connected as a conventional amplifier with the output signal appearing at the plate. The output signal is coupled to the controlled amplifier V210.

As mentioned above, amplifier tube V210 is permitted to function only when the conduction of current of tube V208B is reduced by the switching action of the Eccles-Jordan trigger circuit. When a sferic triggers the Eccles-Jordan circuit, current flow through the cathode resistor of V208B is considerably reduced. The signal from the Wien-Bridge oscillator on the grid of V210 is allowed to be amplified and appear at the plate of tube V210.

Prior to this switching action, tube V210 is cutoff by the current flow of tube V208B through R243, and the signal from the Wien-Bridge oscillator cannot appear at the plate of tube V210. At the instant that triggering occurs in the Eccles-Jordan circuit, the amplified signal from the Wien-Bridge oscillator appears at the plate of V210 and is coupled on to the next amplifier, tube V212B. Tube V212B is connected as a conventional amplifier, and merely amplifies the Wien-Bridge oscillator signal before feeding it on to the reset-pulse generator.

The schematic of the reset-pulse generator is shown in Figure 5. The generator functions to provide a precise time delay between the oscilloscope presentation of two successive sferic recordings. The delay time must be independent of the sferics which happen to occur within the time delay interval or multiple and overlapping recordings will result.

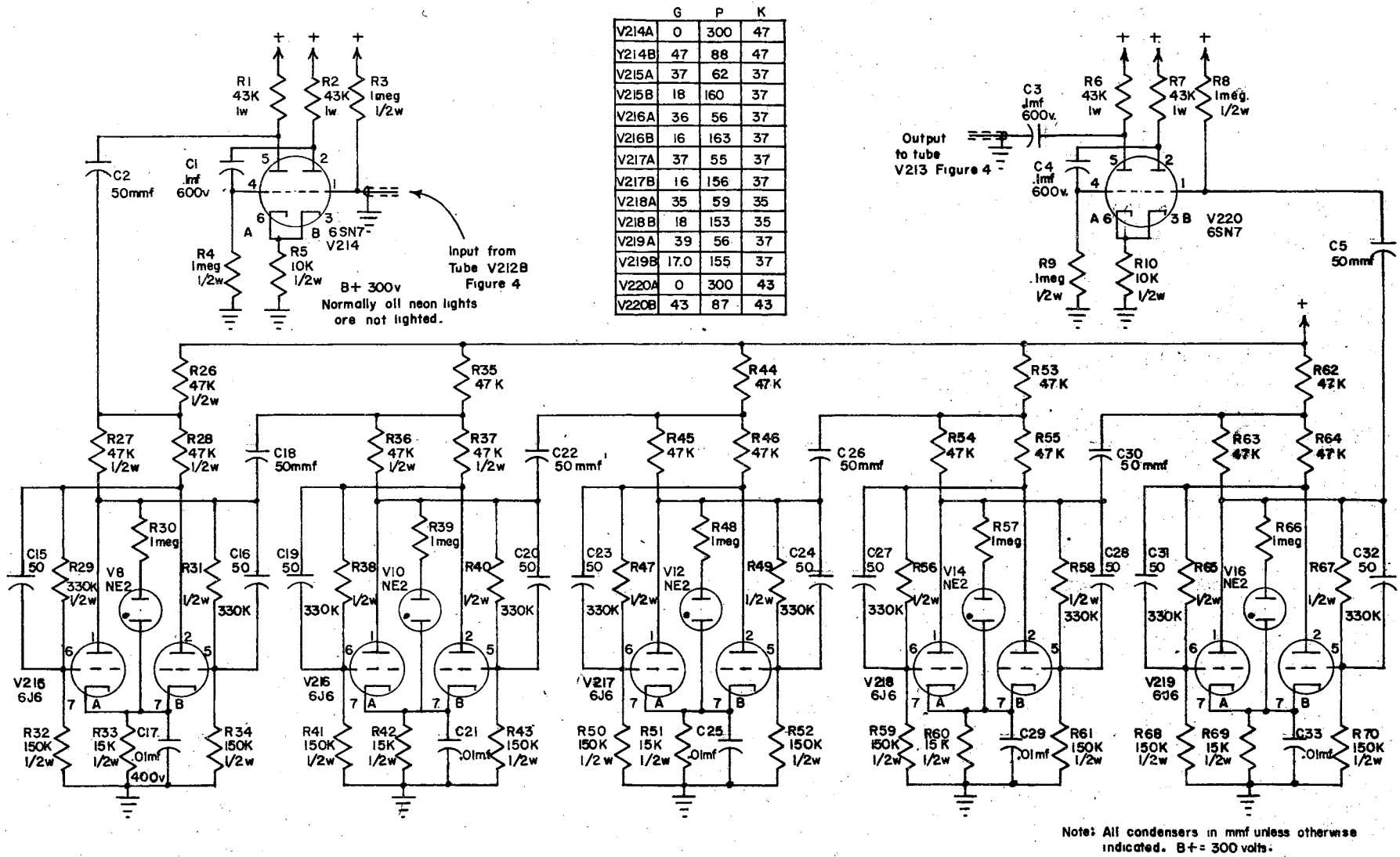


Figure 5. Circuit diagram of the Reset-Pulse Generator.

The unit is an integral part of the electronic photographic synchronizer. Five Eccles-Jordan trigger circuits are employed as electronic counters and 32 input pulses are required before a single output pulse is obtained. In each circuit, an input pulse is applied to both plates simultaneously by a small condenser connected to the common resistor in the plate circuit. The first input pulse causes the Eccles-Jordan trigger circuit to switch from the existing stable state to the other stable state of operation, while the second input pulse returns the circuit to its original conducting state. The output is taken directly from the plate of one tube and fed to the input of the next Eccles-Jordan circuit. Thus, with five of these circuits connected in sequence, a total of thirty-two input pulses is required to produce one output pulse. A one-shot multivibrator<sup>8</sup> is employed as the input circuit of the unit to provide a rectangular impulse of proper shape for triggering the first Eccles-Jordan circuit. An identical circuit is provided as the output stage for isolation purposes.

The input to the reset-pulse generator is the Wien-Bridge oscillator signal from tube V212 (Figure 4). With the arrival of the thirty-second cycle of this signal, an output impulse is generated by the one-shot multivibrator tube V220, and this pulse is fed by coaxial cable to V213 (Figure 4). This output pulse serves to trigger tube V207B in the photographic synchronizer into conduction, causing the circuit to return to its original state. This return completes the chain of events that takes place in the photographic synchronizer unit each time a sferic waveform is selected for oscilloscope presentation.

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<sup>8</sup>Radar Electronic Fundamentals (Washington, 1947), p. 197.

At the instant the output from the reset-pulse generator occurs, the photographic synchronizer is automatically reset and awaits the arrival of the next sferic to be presented.

The waveform sweep generator, shown in Figure 6, is initiated by the positive pulse from tube V209 in the photographic synchronizer. The circuit<sup>9</sup> is a modified version of the type used in the AN/APQ-13A radar. The unique circuit, utilizing a boot-strap sweep generator<sup>10</sup> and a limiting arrangement, provides a constant amplitude sweep voltage regardless of the sweep duration. The primary advantage is that a linear sawtooth wave, whose duration can be precisely set to certain pre-determined values, is generated. A switch is provided whereby any one of six different sweep speeds can be selected. The six sweep speeds available are 200, 500, 1000, 2000, 5000, and 10,000 microseconds; and the particular speed selected is indicated in coded form on the film recording. The sweep speed can be selected by switch S301 and no additional adjustment is required.

The positive pulse arriving at the grid of tube V301 is an indication that a sferic waveform has triggered the photographic synchronizer and that a sweep is needed for the presentation of the waveform on the oscilloscope. Tube V301 functions to couple this impulse into the circuit of tube V302. Tubes V302A and V302B are connected as a one-shot multivibrator that generates a positive rectangular output pulse upon being triggered. The duration of this rectangular pulse would be greater than 10,000 microseconds were it not terminated

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<sup>9</sup>Handbook of Maintenance Instructions for Radio Sets AN/APQ-13 and AN/APQ-13A, St. Louis, 1945), pp. 4-33--4-39.

<sup>10</sup>Britton Chance, pp. 267-269.

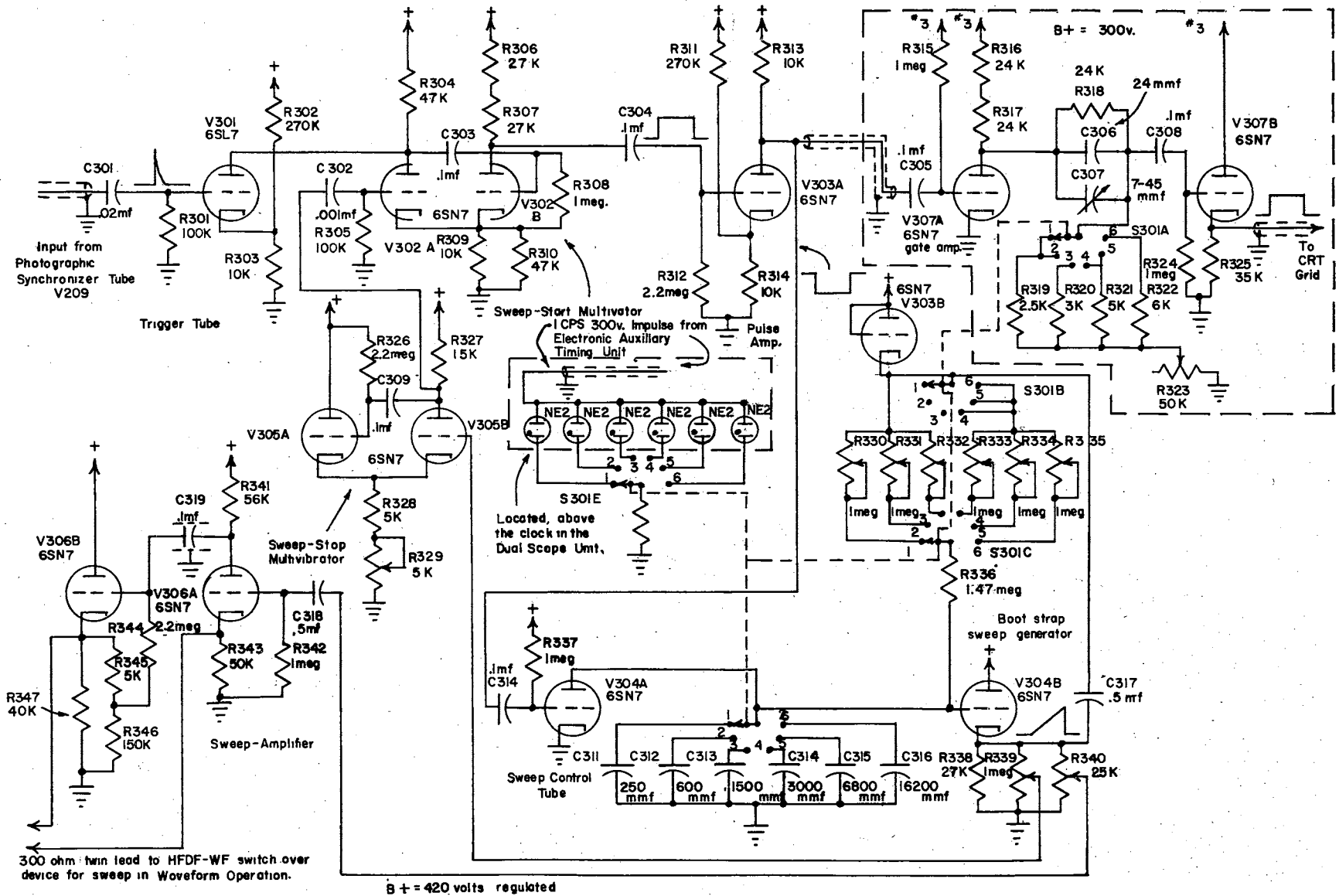


Figure 6. Circuit diagram of the Waveform Sweep Generator and of the Gate Amplifier.

by the application of a negative sweep-stop pulse to the grid of V302A. The generation of this sweep-stop pulse will be discussed in a subsequent paragraph.

The positive rectangular output pulse is coupled from the plate of V302B into the grid circuit of tube V303A. This action produces a negative rectangular pulse at the plate of tube V303A. The negative rectangular pulse is coupled to the grid of tube V307A and to the grid of tube V304A. Tube V307A is a gate amplifier tube whose purpose will be discussed in the next paragraph. Tube V304A is connected in a manner which prevents the functioning of the bootstrap sweep generator, tubes V303B and V304B, until the negative rectangular pulse arrives at its grid.

The negative rectangular pulse drives tube V304A to cut-off and allows its plate potential, which is also the grid potential of tube V304B, to begin rising. Switches S301-B, S301-C, and S301-D select a capacitor and a resistor which govern the rate at which the potential on the plate of V304A rises. The potential across the capacitor rises in an exponential manner toward the positive potential of the power supply were it not for the so-called "boot-strap" arrangement.

Tube V304B in the boot-strap circuit is a cathode follower. As its grid potential tends to rise, the output from its cathode tends to rise in a like manner. The output from the cathode of V304B is coupled to the cathode of tube V303B by condenser C317. This coupling action tends to raise the voltage toward which the RC circuit is tending to charge. Thus, instead of the voltage rising in an exponential manner, it tends to rise in a linear manner. The circuit arrangement tends almost to pull itself up by the "boot-straps"

which accounts for its name. The result of this boot-strap action causes the potential at the grid and at the cathode of tube V304B to rise in a linear fashion.

A portion of this voltage is fed by resistor R339 in the cathode of V304B back to the grid of tube V305B. This is the feedback circuit that stops the sweep. The mono-stable multivibrator, tubes V305A and V305B, are rightly called the sweep-stop multivibrator. When the linearly rising voltage on the grid of tube V305B reaches the critical value, a negative impulse is generated at its plate circuit. This negative impulse, when coupled back to the grid of tube V302A, stops the sweep circuit, resetting the entire unit in preparation for the next spheric to be recorded.

The termination of the sweep causes all tubes to revert to their normal conducting state. The complete cycle results in the generation of a sawtooth signal at the cathode of tube V304B. A portion of the sawtooth signal at this point is fed by resistor R340 to the sweep amplifier consisting of tubes V306A and V306B.

The sweep amplifier must be capable of handling a variety of sweep speeds. For this purpose, the special circuit of a phase-splitter and a cathode follower were developed. The output signal from the cathode circuits of V306A and V306B consists of a positive and a negative sawtooth signal, respectively. This signal is coupled by means of the waveform high frequency direction-finder switchover unit to the horizontal deflection plates of the cathode-ray tube for push-pull deflection of the electron beam.

The above action completes the cycle of events necessary to generate a sweep deflection voltage. Even so, as will be shown, a signal



is also produced, which is amplified and applied to the electron gun of the cathode-ray tube to turn on the electron beam. This signal is referred to as the gating signal, in that it gates the electron beam on in synchronism with the generation of the sweep. The same negative rectangular pulse that is fed to tube V304A to generate the sweep is applied to the grid of tube V307A, the gating-pulse amplifier. The output from the plate of tube V307A is a negative rectangular pulse, which is coincident with the sweep signal.

The coupling circuit between tubes V307A and V307B insures a perfect rectangular waveshape regardless of the sweep speed. On the more rapid sweep speeds, tilt of the top of the rectangular pulse as a function of time is no real problem. When the longer sweep speeds are employed, however, some method must be used to prevent this tilting tendency. In addition to preventing tilt, the circuit also compensates for the higher frequency components to maintain the corners of the rectangular pulse truly square. The brightness of the oscilloscope trace increases with increased magnitude of this rectangular pulse and with longer sweep speeds. So that a consistent presentation for photographic purposes can be maintained, a provision is made to reduce the magnitude of the rectangular pulse for the longer sweep speeds. This function is performed by switch S301A. Resistor R323 allows the making of an optimum adjustment that satisfies all sweep speeds for a given setting of the intensity and focus controls of the cathode-ray tube.

Tube V307B is a cathode follower which feeds the negative rectangular gating pulse by way of the coaxial cable to the cathode of the cathode-ray tube. A negative signal on the cathode of the cathode-ray tube serves to turn on the electron beam and thus produce a display at

the face of the tube. Since the gating pulse, the sweep signal, and the waveform all occur simultaneously, the cathode-ray tube display is a plot of the waveform voltage as a function of time.

Figure 7 is presented to show the relative times of occurrence of the various signals throughout the electronic waveform recorder. The continuous plot of the waveform antenna signal is shown in Figure 7g. It can be seen that as the initial part of the first waveform passes the trigger level of the photographic synchronizer, the cycle of events begins for presenting that waveform oscillographically. Occurring simultaneously are the switching of the Eccles-Jordan trigger circuit, the sweep-start impulse, the sweep, the cathode-ray tube gating pulse, and the train of thirty-two pulses going to the reset-pulse generator. A portion of the waveform is presented on the face of the cathode-ray tube corresponding to the sweep speed in use. At the end of the sweep interval, the sweep-stop impulse is generated.

It should be noted that the next two succeeding waveforms have amplitudes that surpass the tripping level. Nevertheless, they are not presented on the oscilloscope because the Eccles-Jordan circuit has not been reset by the reset-pulse generator. As indicated in Figure 7h and Figure 7i, the train of thirty-two pulses has not completed and the reset pulse has not been generated until after the third waveform. However, the circuit has been reset in ample time to insure presentation of the fourth sferic waveform. The ninth and tenth waveforms occur at a time when the circuit is able to present them, but each is of too small an amplitude to reach the trigger level. The eleventh waveform is the next sferic of sufficient amplitude to trigger the circuit.

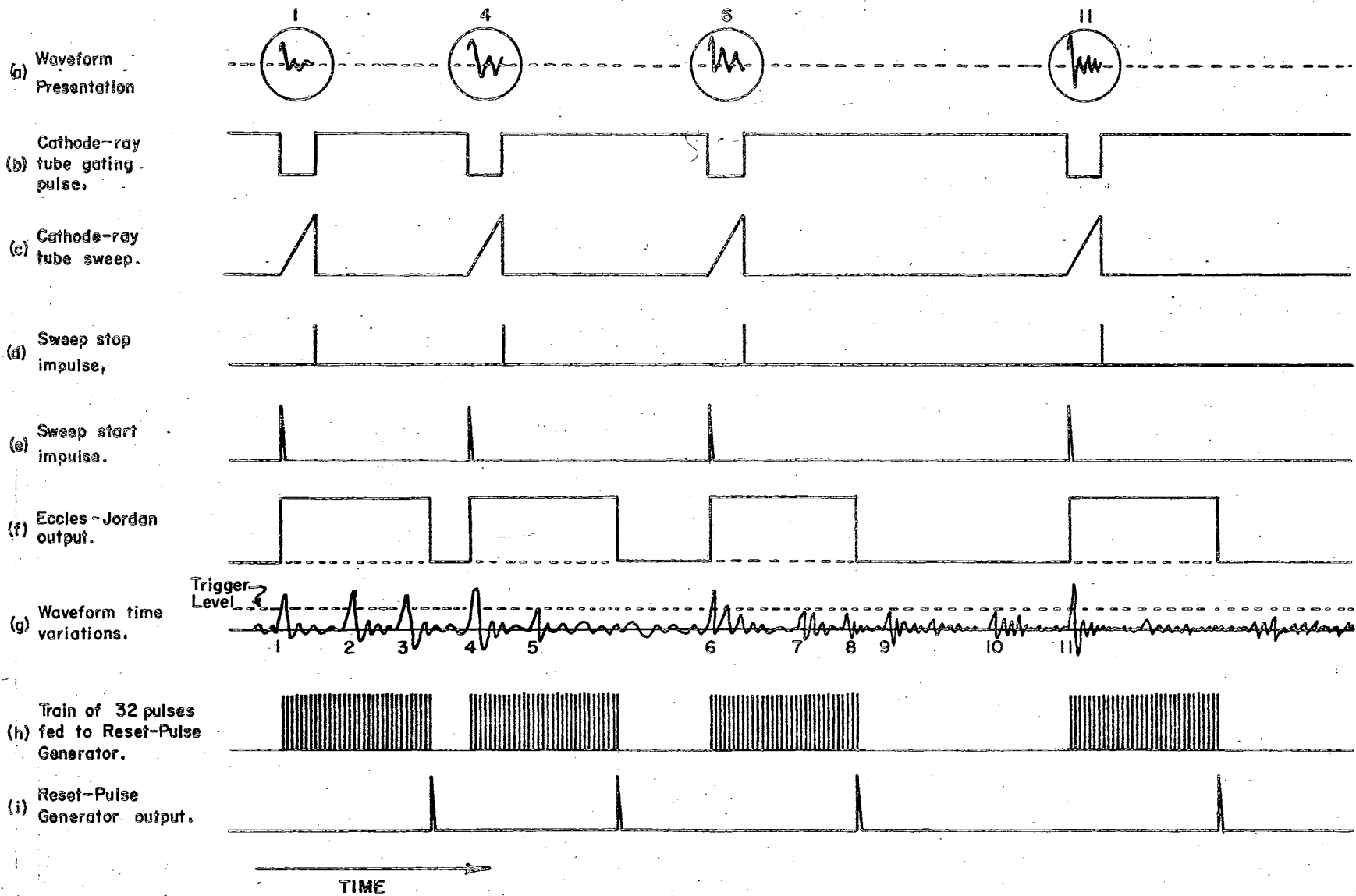


Figure 7. Time-voltage variations of signals generated by the Photographic Synchronizer to present sferic waveforms.

## CHAPTER III

### THE DUAL SCOPE UNIT

The first major project of the research program was the design and construction of a dual cathode-ray tube oscilloscope to present simultaneously the direction of sferics from the AN/GRD-1A and the waveform of sferics from the antenna cathode follower. The side view of the unit is shown in Figure 8.

A test setup was first employed to find the optimum camera position for presenting the required data on the 35 mm film. The light box was next constructed to fulfill these requirements. The camera is mounted on a wooden shelf, so that the front of the camera is 29 1/2 inches removed from the face of the dual scope unit. One disadvantage of the old photographic system was the difficulty in adjusting the oscilloscope controls for photographic purposes. The door to the light-tight box had to be opened to adjust the controls; and often after it was closed, it would be discovered that the adjustments were not proper in the darkened box.

In order to eliminate this difficulty, the dual scope unit was designed for oscilloscope control from the camera position while viewing the cathode-ray tube screens through a peephole. The control shafts extend the full 29 1/2 inches from the panel beneath the camera shelf to the front panel of the dual scope unit. The control knobs of the dual scope unit are provided with screw driver slots that engage with screw driver tips on the end of each long control shaft. This

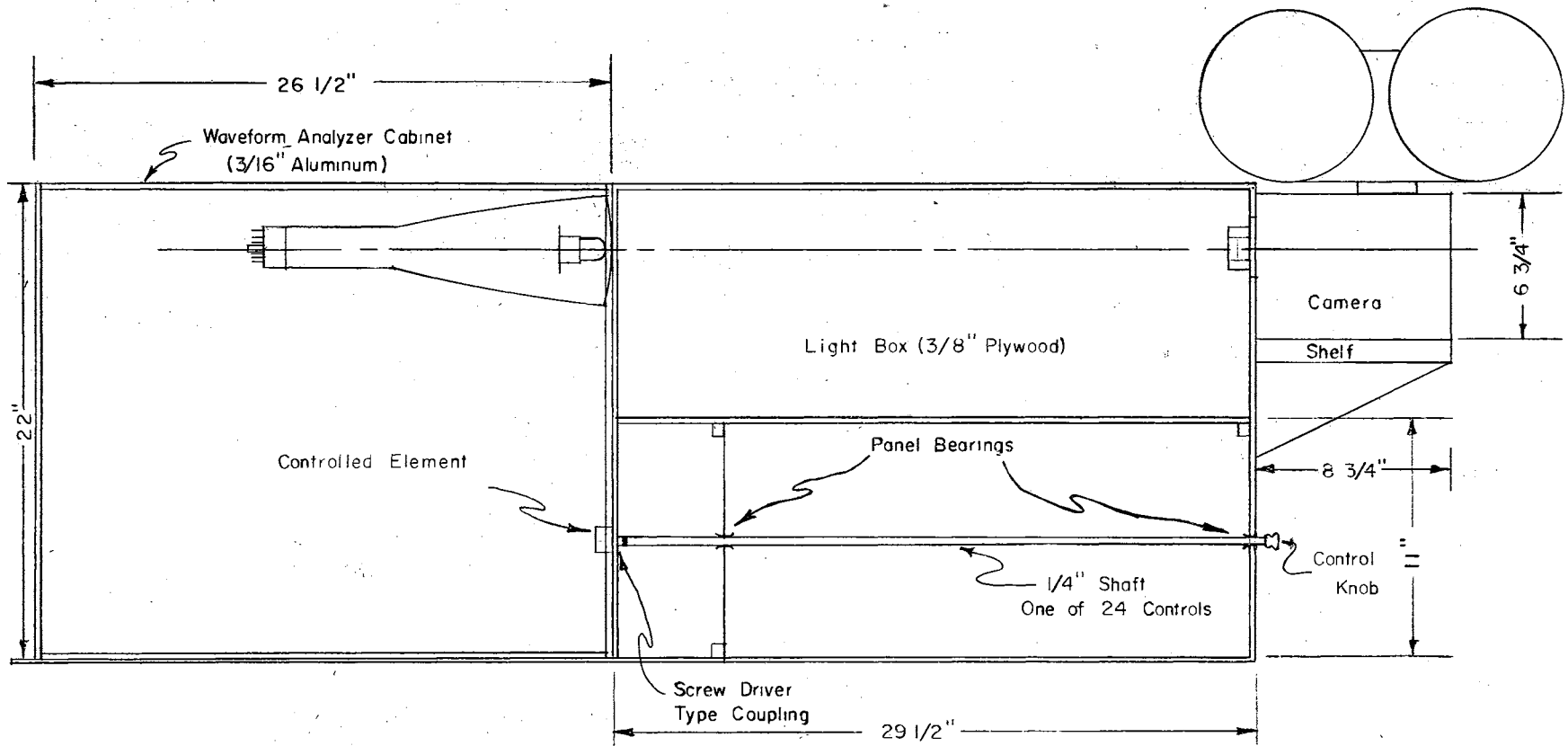


Figure 8. Side view of the Dual Scope Unit.

feature also enables the dual scope unit to be easily removed for repairs and modifications. The front panel of the dual scope unit is securely held in light-tight contact with the light box by two 1/4 inch knob-type bolts. The control panel has provisions for 24 control shafts. However, only eighteen are in present use, leaving plenty of room for modifications and additions to the control panel.

The portion of the dual scope unit that is in the camera field of view is indicated in Figure 9. Although the film digital counter is no longer in use, each one-second interval on the film contains information which gives the time, date, waveform sweep speed, 1 cps coincidence mark, 90° azimuth rotation code, time code for the optical camera, and optical camera azimuth code. An additional tube is flashed at a ten-cycle per second rate when the timer from the AN/GRD-1A is being used. This subject will be discussed later in the chapter. It is necessary to illuminate the clock and date card for an extremely short period of time in order to prevent the film record from showing a smeared image resulting from film travel. This is accomplished by employing a flasher tube similar to the type used in the photoflash units of commercial photographers. A brilliant flash of white light is produced that presents a sharp image of the clock and date card at one-second intervals along the film.

The waveform sweep speed is indicated by the series of six small neon lights located directly above the clock. One of the neon lights is flashed simultaneously with the clock and date card recording. The resulting film record possesses an exposed area adjacent to the upper row of numbers on the clock face. These numbers represent the six available sweep speeds of 200, 500, 1000, 2000, 5000, and 10,000

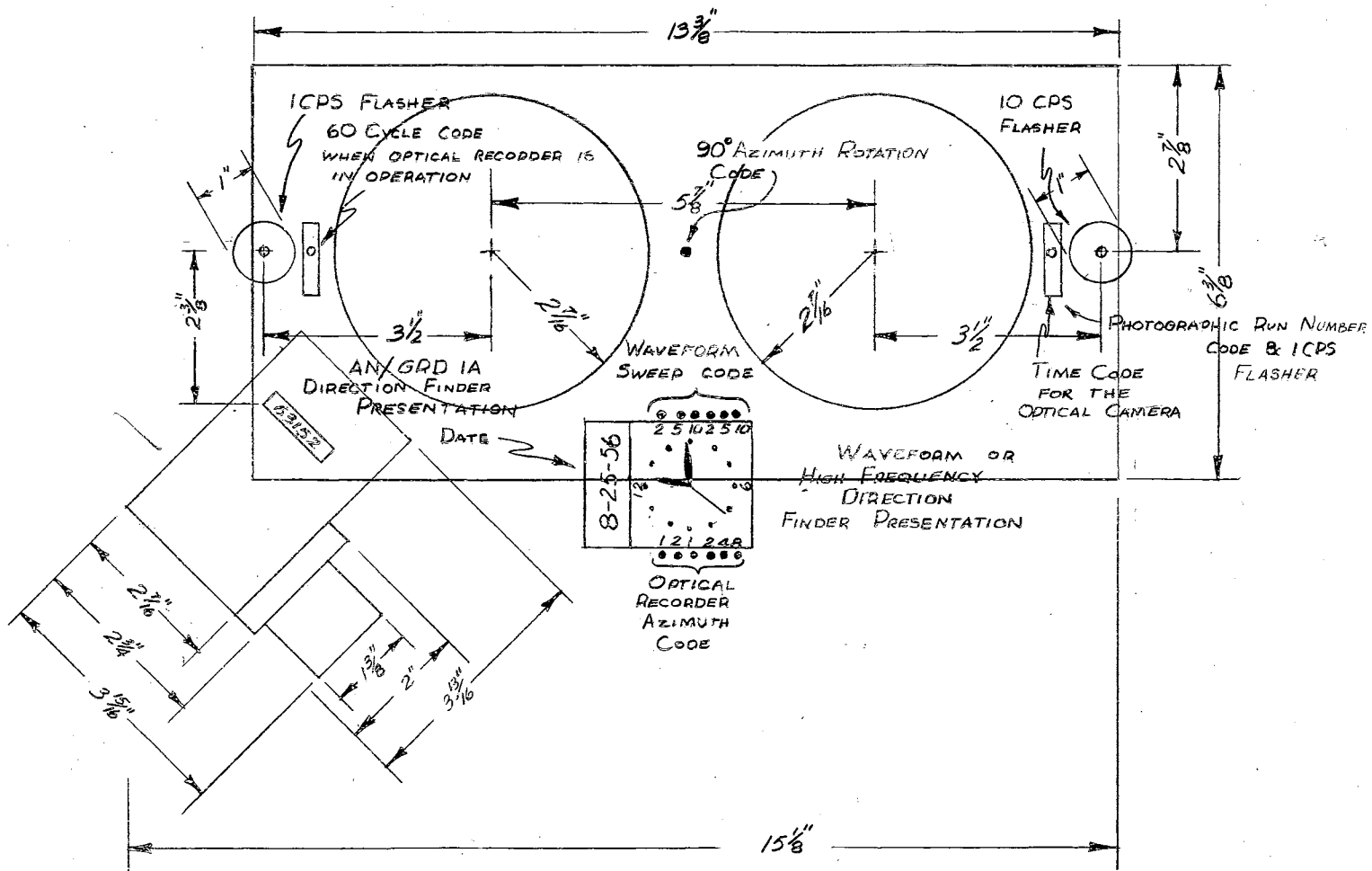


Figure 9. Front panel layout of the Dual Scope Unit.

microseconds. The numbers 2, 5, 10, 2, 5, 10 from left to right on the clock face correspond respectively to the six sweep speeds. The light that is flashed is selected by switch S301E to correspond to the particular sweep speed. Switch S301E is in the sweep generator whose schematic is shown in Figure 6 of Chapter 2. The one-cycle per second flasher, to the left of the AN/GRD-1A scope presentation, provides a time reference adjacent to the scope presentation that corresponds to the time indicated by the clock. This feature is desirable, for the clock indication is displaced on the film record from the corresponding spheric recordings.

The right-hand cathode-ray tube can exhibit either the waveform or the high frequency direction finder presentation. When the scope is presenting the HFDF, the azimuth orientation can be selected to indicate north to the left or north to the top of the cathode-ray tube. A clockwise arrangement of the cardinal points north, east, south, and west is employed in each case; however, some indication must be recorded in order to distinguish the two orientations on the film. This recording is accomplished by flashing the 90° azimuth rotation code light, located between the two scope tubes, when the orientation is such as to place north at the top of the cathode-ray tube. This neon light is flashed at one-second intervals simultaneously with the clock. The light is controlled by the 90° azimuth rotation unit which will be discussed in detail in Chapter IV.

The time code for the optical camera is necessary when simultaneous photographic records are being made of the lightning discharge itself and of the spherics arriving at the antenna of the electronic detection equipment. The operator of the camera which photographs the actual



stroke has control over the waveform analyzer camera. Simultaneous time markings are required on each film for proper correlation. Using a four character code and a sending key, the operator of the optical stroke recorder also uses the same neon light to indicate the number of the photographic run.

An exposed strip is placed down the side of the film to exactly correspond to the time that simultaneous pictures are being made. A group of six neon lights, located just below the clock, are used to code the azimuth at which the optical camera is pointing. When the operator throws the switch to start the optical camera motor, the motor of the waveform analyzer is also started, and the neon light directly to the left of the AN/GRD-1A presentation is excited with a sixty-cycle voltage. This action places the exposed strip down the film record of the waveform analyzer camera. A detailed description of the unit used for coding the film during operation of the optical stroke recorder is given in Chapter VI.

The optical recorder azimuth code, located beneath the clock, indicates the direction in which the optical camera is pointed to the nearest ten degrees. The first two lights on the left represent 100 and 200 degrees, respectively. Any combination of these two lights can be flashed to correspond to 0, 100, 200, or 300 degrees. The remaining four lights represent 10, 20, 40, and 80 respectively, from left to right. Any combination of these can be flashed to indicate 10-degree intervals from 0 to 100. A combination of the six lights can be flashed to represent any one of the thirty-six 10-degree intervals of orientation from 0 to 350 degrees.

### Dual-Scope Power Supplies

The most bulky part of the entire laboratory is the immense power supply system required to furnish the plate circuits of all the tubes in their respective functions. It has been a tremendous problem to provide power supplies for the greatly increased number of electronic circuits at the laboratory. The circuits associated with the dual scope unit are no exception. Sixteen power supplies are necessary for the equipment required to present the dual scope display. Even the preliminary design indicated that the physical size of the power supply system would greatly exceed the volume available in the dual scope cabinet; and, therefore, all power supplies are located externally. A multitude of cables terminate on the rear panel of the dual scope unit to channel the power to the respective units.

The long power transmission line from the city of Stillwater to the Tornado Laboratory causes an undesirable amount of voltage fluctuation because of its length and the diurnal variation in customer load requirements. To offset this effect, the majority of the power supplies at the Tornado Laboratory are of the regulated output type. There is one exception to this practice; the high-voltage power supplies for the cathode-ray tubes are of the conventional type without regulating features.

The schematic of the high voltage power supply for the cathode-ray tubes of the dual-scope unit is shown in Figure 10. The positive and negative high voltages necessary for the electron gun of the cathode-ray tubes are provided by rectifier tubes V401 and V402, respectively. Two coaxial cables are used to connect these voltages to the dual scope unit. Because of the frequent failure of the high voltage transformers

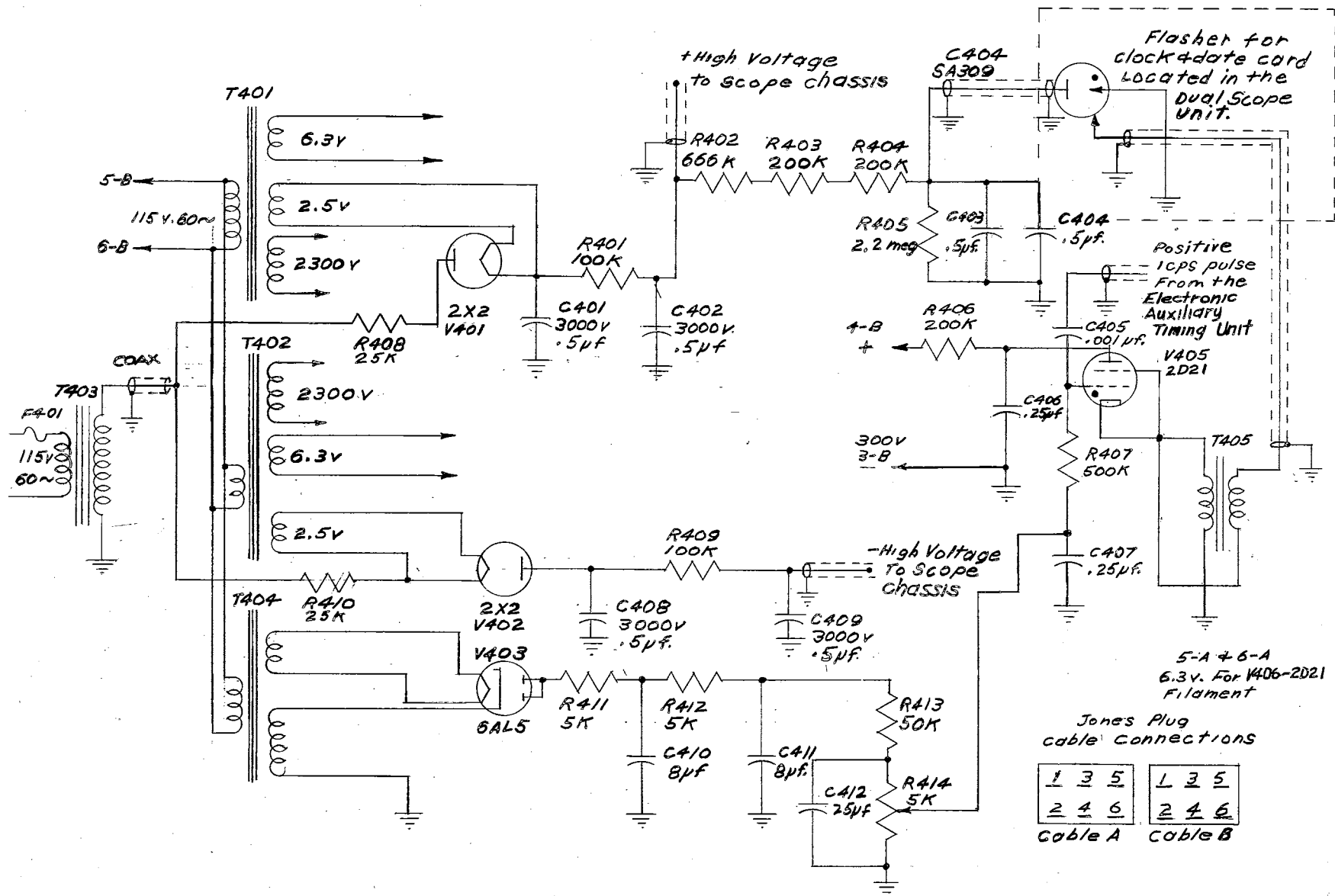


Figure 10. Circuit diagram of the clock and date card flasher and the high voltage supply for the cathode-ray tubes of the Dual Scope Unit.

T401 and T402, an auxiliary chassis is provided to mount a single transformer with a high voltage winding capable of supplying both rectifier circuits. The high voltage a. c. is fed by coaxial cable to the plate of V401 and to the cathode of V402. Resistors R408 and R409 act to limit the transformer current should a fault occur in the high voltage circuit. The fuse in the primary circuit of transformer T403 provides additional protection in case of faults.

The schematic of the clock and date-card flasher unit is also shown in Figure 10. A 14,000-volt impulse is generated by tube V405 for firing the clock flasher tube. Tube V405 is a thyratron, biased to be normally in the non-conducting state. The bias voltage is supplied by rectifier tube V403. A positive 1-cps pulse is applied to the grid of tube V405, causing the tube to fire. The bias control potentiometer R414 should be adjusted to prevent tube V405 from firing except when the 1-cps pulse is applied. Firing of the gas tube V405 produces a momentary pulse of current through the primary winding of transformer T405 located in the cathode circuit. Condenser C406 in the plate circuit insures that the tube will conduct only momentarily. The conduction of tube V405 quickly discharges condenser C406 to such a point that tube current ceases; and the condenser cannot recharge quickly because resistor R406 limits the current. Thus, the grid of tube V405 regains control of plate conduction, and another impulse of plate current does not exist until the occurrence of the succeeding 1-cps impulse. The electronic auxiliary timing unit generates the 1-cps impulse and is discussed in a subsequent paragraph of this chapter.

A 14,000-volt impulse is generated each time tube V405 conducts and is fed to flasher tube V404 by a coaxial cable. Tube V404, an

experimental type SA309, is similar to the ones used by commercial photographers. The resistor-condenser combination, consisting of R402, R403, R404, R405, C403 and C404, provides approximately 800 volts at the plate of tube V404 prior to the flashing operation.

The 14,000 volt impulse is applied to a metal strap surrounding the flasher tube and results in the immediate production of a brilliant flash of light of very short duration. The conduction of the flasher tube discharges condensers C403 and C404 so rapidly that the resulting flash of light exists only for a few microseconds. The occurrence of this short duration flash of light at a 1-cps rate causes a photograph of the clock and date card to appear at regular intervals along the film record.

#### The Electronic Auxiliary Timing Unit

In the original application of the dual scope unit, the 1-cps signal, used to place time markers on the film record, was controlled by the timer deck in the AN/GRD-1A direction finder. The function of the timer deck has been transferred to the electronic auxiliary timing unit. A brief description of the timer deck will be presented since it is used for emergency or special purposes.

When several AN/GRD-1A direction finders are used in a triangulation method for storm detection, synchronized time markers are placed on each film record so that the time of each sferic can be determined. The timer deck functions to produce the necessary timing marks. The timer deck derives its reference signal from a 440-cycle tuning fork whose oscillating frequency is adjusted to synchronize with that from the Bureau of Standards Station WWV.

A 440-cycle synchronous motor is controlled by a signal derived from the tuning fork. A gear reduction box on the motor rotates a cam which closes a microswitch at a 1-cps rate. The microswitch can be rotated, relative to the cam, so that its closure can be synchronized with the 1-cps signal from Station WWV. When the operators at all stations of the triangulation network perform the synchronizing adjustments, the time markers on the film from all stations correspond in time relationship. Two additional cams are provided on the gear box shaft to generate 10-cps time markers and to operate a Veeder-Root counter at a 1-cps rate.

The noise level produced by the 440-cycle motor in the timer deck is excessive. Upon the failure of a bearing in the motor, the duties of the unit are transferred to an electronic timer which functions quietly.

The schematic of the electronic timer, which is called the electronic auxiliary timing unit, is shown in Figure 11. The basic function of the unit is to cause a plate-current relay to energize momentarily at a 1-cps rate. The contacts of the plate-current relay are connected to replace the action of the 1-cps time-marker microswitch described above. No attempt is made to operate the 10-cps flashers or the Veeder-Root counter, because the presense of these two operations is not necessary for a one-station analysis of film records as employed at the Tornado Laboratory. The timer deck is retained for emergency use in case of failure in the electronic auxiliary timing unit or for use when an additional experimental laboratory is operating in conjunction with the Tornado Laboratory.

The timer deck has been removed from the AN/GRD-1A direction

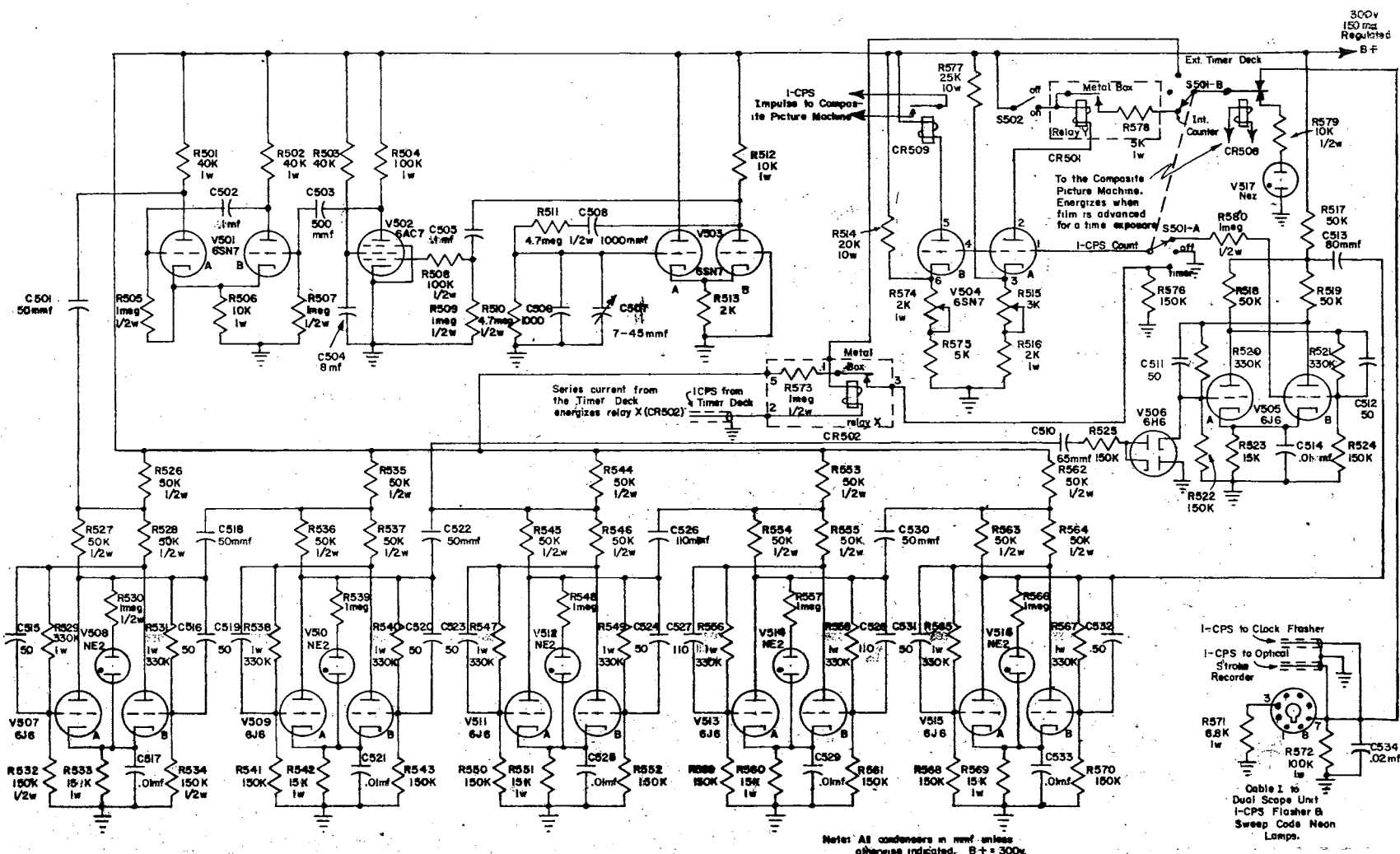


Figure 11. Circuit diagram of the Electronic Auxiliary Timing Unit.

finder cabinet and relocated in the radar van. The noise created by the timer deck motor is of no consequence in the radar van, where a considerable amount of noise already exists. Coaxial cables are employed to connect the microswitch contacts in the timer deck to the electronic auxiliary timing unit inside the Tornado Laboratory. A switch on the auxiliary timing unit is provided to select either timer for controlling the flasher lights.

The action of the electronic auxiliary timing unit is based upon the ability of Eccles-Jordan trigger circuits to function as binary counters. A group of five trigger circuits is connected in series, and the output from a thirty-two cycle per second oscillator is fed to the input of the first trigger circuit.

The frequency existing at the output of the fifth trigger circuit is one cycle per second. This 1-cps signal is used to control the energizing of the plate current relay CR501. A signal from the second trigger circuit, whose output frequency is eight cycles per second, is used to de-energize the plate-current relay. The relay action, with both the 1-cps and the 8-cps signals applied, is that an energized state exists for one-eighth of a second at one-second intervals. The result just described is the required action, the relay energizing momentarily at a 1-cps rate.

Referring to the electronic auxiliary timing unit schematic in Figure 11, tube V503 is connected as a Wien-Bridge oscillator for generating a 32-cps signal. Tube V502 is a wave-shaping isolation amplifier between the oscillator and the one-shot multivibrator tube V501B. The output of the one-shot multivibrator from the plate of V501B is coupled to the first Eccles-Jordan trigger circuit, tubes



V507A and V507B.

Tubes V509A and V509B form the second trigger circuit from which the 8-cps relay control signal is derived as well as the signal to the third trigger circuit. The third, fourth, and fifth trigger circuits utilize, respectively, both sections of tubes V511, V513, and V515. Tubes V508, V510, V512, V514, and V516 are neon indicator lamps, which flash in accordance with the various frequency signals present in the respective trigger circuits. Failure of the neon tubes to flash properly indicates a fault condition.

The two sections of tube V505 are also connected as an Eccles-Jordan trigger circuit. Prior to the arrival of the 1-cps signal from tube V515, tube V505A is conducting and tube V505B is non-conducting. The grid of tube V504 is connected to the grid of tube V505B to insure a similar conduction current in the respective tubes; thus under the conditions prior to the 1-cps pulse, tube V504 is non-conducting. Relay CR501, which is in the plate circuit of tube V504, energizes when tube V504 is conducting and de-energizes when it is non-conducting.

The application of the 1-cps impulse from tube V515B reverses the conduction roles of the two sections of tube V505 making V505B the conducting section. This action causes the relay control tube V504 to conduct and energize the plate relay CR501. The positive impulses, coupled into the grid of tube V505A every one-eighth second from the second Eccles-Jordan trigger circuit, cause the sections of tube V505 to revert to their normal state in which V505A is the conducting section. This cycle of events results in tube V505B as well as the relay control tube V504 being in the conducting state for exactly one-eighth of a second. Exactly one second later the cycle repeats

itself. The end result is the energizing of relay CR501 for periods of one-eighth second at a 1-cps rate. This action is the desired action.

Resistor R515 in the cathode of tube V504 should be adjusted to give consistent contact action of the plate relay CR501.

The contacts of relay CR501 apply 300 volts to all neon flasher tubes and to the grid of the thyatron, which controls the clock flasher shown in Figure 10. Circuit connections of the small neon flashers, type NE-2, are all similar. The circuit connections shown in Figure 6 are for the group of neon flasher tubes that indicate sweep speed.

Switch S501 is provided to select the operation of either the electronic auxiliary timing unit or the timer deck in producing the timing markers on the film record. The 10-cps flasher tube is permanently connected to the timer deck unit and operates whenever power is supplied to the timer deck.

#### The Dual Scope Cathode-Ray Tube Circuit

The circuit used for the cathode-ray tubes in the dual-scope unit is shown in Figure 12. There is nothing unusual about the schematic except the switching circuits which are necessary to provide the 5RP11 cathode-ray tube with two modes of operation and the relays which are employed to produce time-exposure of the oscilloscope presentations. Conventional voltage dividers are employed to furnish the required potentials to the various elements in the electron guns.

The 5RP11 cathode-ray tube is used to present either the spheric waveform or the high frequency direction finder display. In order to function in the respective capacities, various circuits connections

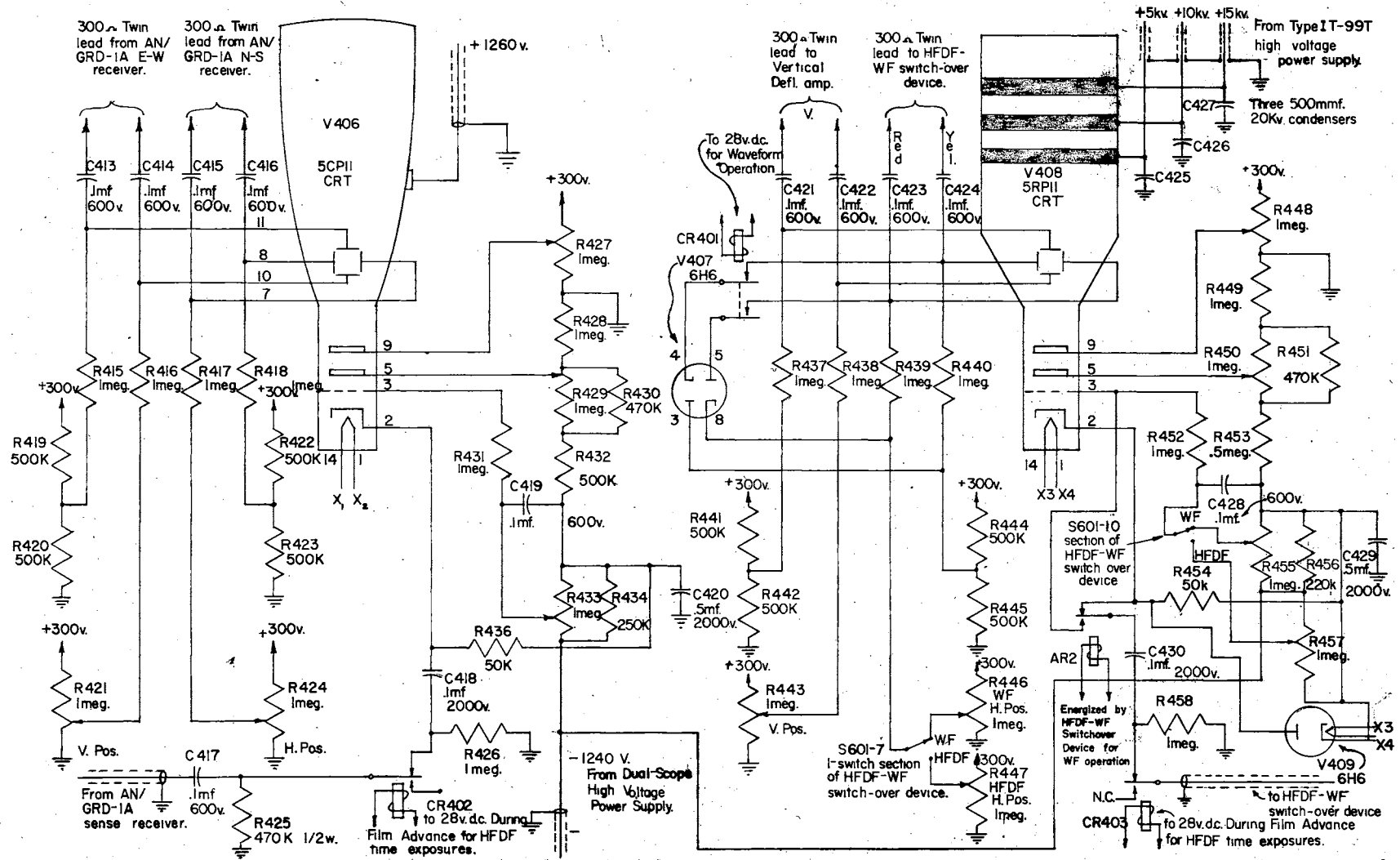


Figure 12. Circuit diagram of the two cathode-ray tubes of the Dual Scope Unit.

must be switched by relay action. A different intensity control setting required for the two modes of operation is selected by switch S601-10. A different horizontal positioning voltage required in the waveform mode of operation is provided by switch S601-7. Clamping circuits are connected into the horizontal deflection plates for the waveform mode of operation by relay CR401.

The signal employed to intensity modulate the electron beam must be disconnected by relay CR403 when the film is being advanced in preparation for a time exposure record. The 5RP11 is a special cathode-ray tube requiring high voltages on the post accelerator electrodes, which are called intensifier bands. In order to produce a very bright image and yet keep the deflection requirements within reasonable limits, almost all of the electron acceleration is produced subsequent to deflection by the graded potentials applied to succeeding intensifier bands. The 5RP11 has three such bands that use potentials of 5,000 volts, 10,000 volts and 15,000 volts, respectively. The three potentials are supplied by a voltage divider located in the IT-99T high voltage power supply.

The power supply uses a high-frequency oscillator and high voltage transformers similar to those found in television sets. Since the high-frequency ripple produces excessive intensity modulation of the electron beam, three 500 mmf, 20 KV condensers are connected to the respective intensifier bands to eliminate this difficulty. The three potentials are applied to the dual scope unit by means of coaxial cables.

The following controls for the 5RP11 cathode-ray tube appear on the control panel beneath the camera shelf: resistor R455, the waveform

intensity control; resistor R457, the high-frequency direction finder intensity control; resistor R450, the focus control; resistor R446, the waveform horizontal positioning control; resistor R447, the high frequency direction finder horizontal positioning control; and resistor R443, the vertical positioning control. Resistor R448, the anti-astigmatism control, is located on the right side of the dual scope unit, near the rear mounting support for the 5RP11 cathode-ray tube.

A short section of 300-ohm twin lead is used to permanently connect the output of the vertical deflection amplifier (Figure 3) into the 5RP11 vertical deflection plates. An additional short section of 300-ohm twin lead is used to connect the 5RP11 horizontal deflection plates into the HFDF-WF switchover device. In the waveform mode of operation, the output of the waveform sweep generator (Figure 6) is connected to the horizontal deflection plates. In the high-frequency direction finder mode of operation, the horizontal deflection plates are connected to the output of a horizontal deflection amplifier, whose schematic is identical to the vertical deflection amplifier (Figure 3). However, a relay, CR503, (Figure 28) is used to reverse the polarity of the output signal in accordance with the 90° azimuth rotation device. The reason for this action will be discussed in the next chapter.

When the unit is in the waveform mode of operation, the electron beam, under control of the sweep signals, starts its linear progression across the screen from the extreme left hand side. A separate positioning control R446 is used to place the electron beam at this left hand starting point. As the linear sweep voltages are applied to the deflection plates, condensers C423 and C424 tend to change

their charge at an exponential rate, which causes the electron beam to deflect in a slight exponential manner. The clamper tube V407, however, prevents the condenser voltages from changing when the sweep voltage is applied. On the short sweep speed, this action is hardly discernable, but if the clamper tube were not present on the longer sweep speeds, the condenser charging current would be objectionable.

Tube V406, the 5CP11 cathode-ray tube, is used to present a display of the AN/GRD-1A direction finder. The voltage divider for its electron gun is identical to that of the 5RP11 cathode-ray tube with the exception that only one intensity control is required. At one time, tube V406 had a dual purpose. The different deflection voltage and gating voltage sources were manually connected and disconnected. In the dual role, tube V406 was connected to display either the AN/GRD-1A direction finder pattern or the sferic waveform. The sferic waveform, displayed by V406, utilized the longer sweep speeds and the regular waveform cathode-ray tube V408 displayed the shorter sweep speeds. In this manner, the initial part of a sferic waveform could be observed in detail, while the longer sweep speed indicated the entire sferic waveform as well as other waveforms that immediately followed. This procedure has been discontinued in favor of records showing both the direction of sferic arrival and sferic waveform.

With only the one mode of operation required, the output from the AN/GRD-1A is permanently connected into the deflection and gating circuits of tube V406. Short sections of 300-ohm twin lead are used to connect the deflection voltages from the loop receivers of the AN/GRD-1A. The output from the AN/GRD-1A sense receiver is fed by coaxial cable to the cathode of tube V406. Relay CR402 is connected in series with the

lead carrying the sense signal. During the interval that the film is advanced in preparation for a time exposure, relay CR402 energizes to remove the sense signal and prevent exposure of the film. The relay is de-energized for the required time exposure and then re-energized before advancing the film for the subsequent time exposure. The circuit on each side of the relay contacts, consisting of C417, C418, R425, and R426, prevent any transient voltages when the relay is operated. The same potential exists at the twopoints being connected and disconnected. In this way transient currents due to charging or discharging condensers are not present to give difficulty.

## CHAPTER IV

### THE HIGH FREQUENCY DIRECTION FINDER

When the author designed and constructed the high frequency direction finder, he never imagined that it would be such a valuable contribution to the research program.

The inability of the original model of the AN/GRD-1A direction finder to respond properly to near-by storms prompted the design of the high frequency direction finder. At the time the design was begun, the AN/GRD-1A had been successfully used to track severe storms that were located relatively distant from the set; however, near-by severe storms could not be located to the desired degree of accuracy because of the excessive number of elliptical oscilloscope presentations. A relatively thin-line presentation of the angular location of storm centers is required before an accurate determination of position can be ascertained.

A number of basic ideas were conceived to make the high frequency direction finder function more consistently on severe storms and be easier to operate and tune than was its predecessor the AN/GRD-1A. In recent years, the Signal Corps has issued modification data for the AN/GRD-1A which makes it conform almost exactly to the high frequency direction finder principles. The present operating characteristics of the two directions finders are very similar.

The deflection requirements of a cathode-ray tube indicate that



elliptical presentations result from the existence of a phase difference between the sine-wave vertical and horizontal deflection voltages. It is evident that any condition which causes time or phase displacement of the deflection voltages will produce elliptical presentations.

A list of some possible causes of elliptical presentation in sferic direction finder equipment is as follows:

1. Two strokes occurring at almost the same instant but at different locations, requiring the direction finder to indicate two directions almost simultaneously.
2. Transformer coupled amplifiers or resistance-capacitance coupled amplifiers, whose frequency response characteristics are not sufficient to handle the pulse-type voltages existing in sferic detection equipment.
3. Electrical coupling between vertical and horizontal deflection systems; for example, magnetic coupling between the loop antennas.
4. The sferic occurring so near to the station that the stroke does not appear to be a point source.

The above list is representative only of the major problems to be considered in the receiver design. Even when the receiver is designed to conform to almost all of the above considerations, a certain number of elliptical patterns persist.

The almost simultaneous occurrence of two sferics at different angular positions from the direction-finding apparatus poses a severe problem. Since the set must provide an indication of one direction and recover quickly enough to provide a satisfactory indication of the second sferic direction, the speed of presentation is most important.

In order to explain the remedy for a given problem, the mechanics of the problem should be presented in such a manner that the problem is obvious. After this matter has been accomplished, the description of the solution to the problem becomes relatively simple. A description of the basic principle upon which spheric direction finders function aids in explaining the design considerations of the high frequency direction finder.

#### Antenna System

The antenna system usually consists of two identical loops normal to one another and orientated in the North-South and East-West directions, respectively, and a vertical whip antenna located nearby. Whenever a spheric occurs, a complex electromagnetic wave which radiates in all directions is generated. As the wave arrives at the receiving set, a signal is induced into each loop antenna as well as into the sense antenna. The amplitude of the signal in each loop depends upon the angular relation between the electromagnetic wave and the plane of the loop; whereas, the voltage induced into the sense antenna is independent of the direction of arrival. The loop antennas are assumed to be perfect circles with the plane of each loop in the vertical direction. The plane of each loop is also orientated to correspond to the four cardinal points as stated above.

When the angle corresponding to due north is designated as zero degrees, the other cardinal points east, south, and west correspond to  $90^{\circ}$ ,  $180^{\circ}$ , and  $270^{\circ}$ , respectively. If the origin of the spheric wave is sufficiently distant from the set, the electromagnetic wave intercepted by the antenna system is essentially plane in nature.

Under these conditions, the voltage induced in the north-south Loop is

$$E_{ns} = E(t)_{sferic} [ \cos \theta ] \quad (a)$$

while that for the east-west Loop is

$$E_{ew} = E(t)_{sferic} [ \sin \theta ] \quad (b)$$

where  $\theta$  is the angle and the sferic origin bears relative to the coordinate system of the loops, and  $E(t)_{sferic}$  represents the time variation in loop induced sferic voltage, which would exist if the sferic origin were in the plane of the loop. A polar plot of the reception characteristics of the antenna system is shown in Figure 13.

#### The Cathode-Ray Tube

The essential parts of a cathode-ray tube employing electrostatic deflection are shown in Figure 14.

The nomenclature illustrated in Figure 14 is used to describe the deflection resulting from a given deflection voltage.

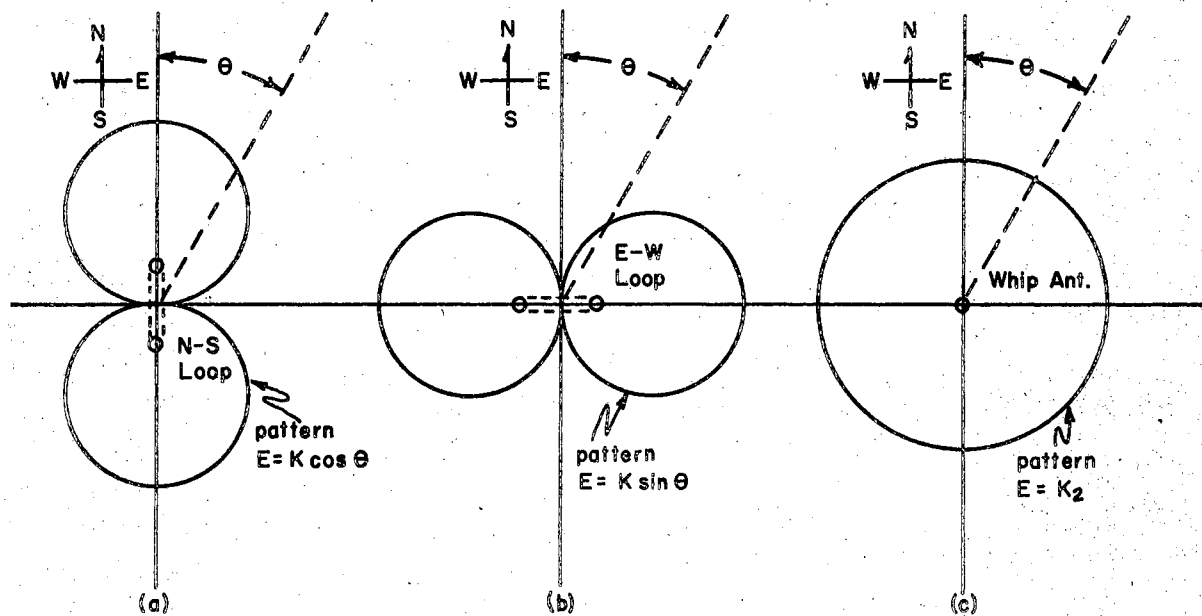
The horizontal velocity  $V_z$  is attained as the electron is accelerated from the cathode to the final accelerating anode through a potential difference of  $E_a$  volts. The resulting velocity is related to accelerating potential by Equation(1),

$$\frac{1}{2}M_e V_z^2 = E_a Q \quad (1)$$

$Q$  is the charge of the electron in coulombs;  $M_e$  is the mass of the electron in kilograms;  $E_a$  and  $V_z$  represent the quantities described above in volts and meters per second, respectively.

The result upon rearranging Equation (1) and solving for the velocity  $V_z$  is

$$V = \sqrt{\frac{2E_a Q}{M_e}} \quad \text{or} \quad \frac{1}{E_a} \left[ \frac{2Q}{M_e} \right]^{\frac{1}{2}} \quad (2)$$



Vertical view of the North-South Loop Antenna and its reception pattern.

Vertical view of the East-West Loop Antenna and its reception pattern.

Vertical view of the Whip Antenna and its circular reception pattern.

Figure 13. Loop and whip antenna reception patterns.

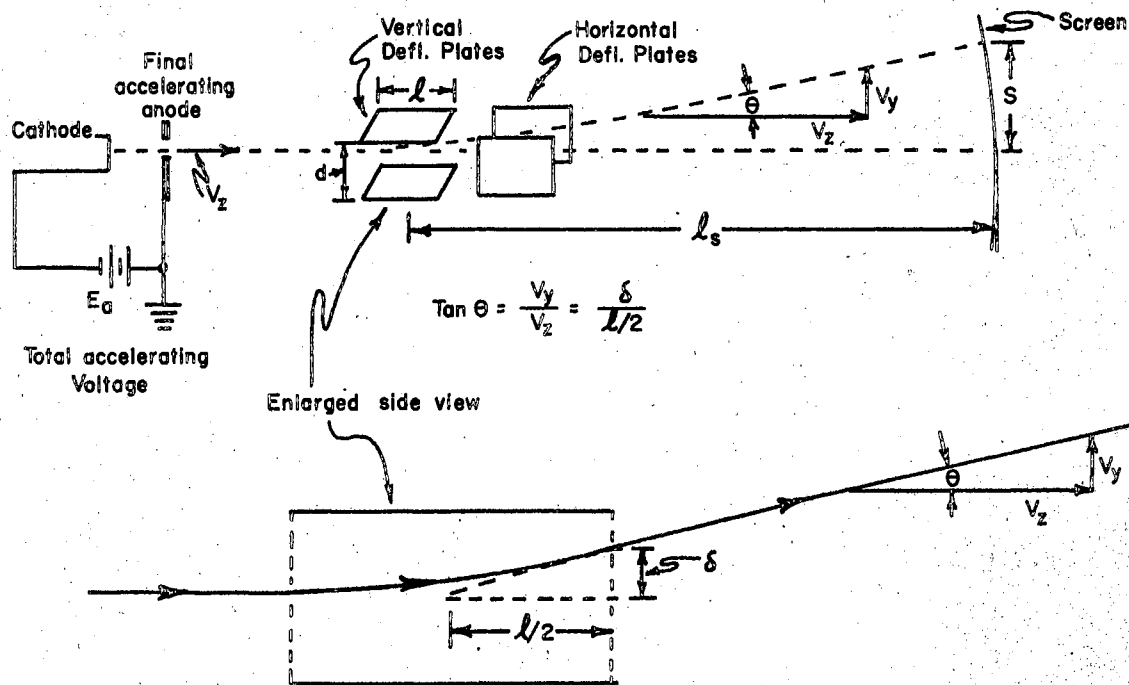


Figure 14. Cathode-ray tube with electrostatic deflection.

Equation (2) shows that the velocity in the Z-axis direction of the cathode-ray tube depends upon the square-root of  $E_a$ , the accelerating potential of the electron gun.

The electron arrives at the region between the vertical deflection plates with the same Z-axis velocity, since there are no retarding forces intervening. A potential  $E_y$  is applied across the vertical deflection plates and establishes an almost uniform electric field in the region between the plates. Practically uniform electric fields exist between parallel plates when the area is large compared to the distance of separation, a fact which is assumed to be the case for the above deflection plates.

There is some slight fringing of the electric field at the edges of the plates, but for reasons of simplification, this fringing will be neglected. If the fringing is not severe, it simply modifies the deflection requirements by a slight amount. The vertical force on the moving electron is constant throughout its travel between the deflection plates. The electron remains in the region between the deflection plates a length of time  $t_p$ , that depends only on the z-axis velocity and the length  $l$  of the deflection plates. The relation

$$t_p = \frac{l}{V_z} \quad (3)$$

gives the time in seconds if  $l$  and  $V_z$  are in meters and meters per second, respectively.

The action of the electric field between the deflection plates results in a vertical acceleration of the electron which exists only in the region between the deflection plates. The result of this accelerating action is a final vertical component of velocity  $V_y$  which causes the electron to emerge at an angle  $\theta$  in reference to the tube axis. The electron strikes the screen of the cathode-ray

tube at a point  $S$  meters removed from the center-line, causing a spot of light at this point. Because of the negative charge of the electron, a positive potential on the top deflection plate relative to the lower plate causes deflection above the tube axis. If the reverse is true, the deflection is below the tube axis. The tangent of the deflection angle  $\theta$  can be calculated from the ratio of the  $y$ -axis and  $Z$ -axis velocities as indicated by Equation (4),

$$\tan \theta = \frac{V_y}{V_z} \quad (4)$$

The velocity  $V_y$  can be evaluated in terms of the vertical deflection plate dimensions and the voltage used to establish the electric field between them. In order to do this, one can start with Newton's second law as applied to the electron in the electric field,

$$f = M_e A \quad (5)$$

Upon solving for the acceleration in Equation (5) and substituting the electrical equivalent of the force on the electron, Equation (5) becomes

$$A = \left[ \frac{QE_y}{d} \right] \left[ \frac{1}{M_e} \right] \quad (6)$$

In Equation (6), the term  $QE_y/d$  represents the force in newtons on the electron which has a charge of  $Q$  coulombs. The force on any charged body situated in an electric field is the product of the charge on the body in coulombs and electric field strength at the given point, expressed in either volts/meter or newtons per coulomb. The electric field intensity existing between parallel plane electrodes whose area is large compared to the distance of separation  $d$  is given by

$$\mathcal{E} = \frac{E}{d} ; \text{ thus the term } \frac{QE_y}{d}$$

in Equation (6) is merely the product  $Q\mathcal{E}$ .

The vertical velocity attained by the electron can be determined

by the integral of Equation (6) as a function of time,

$$V_y = \int \frac{QE_y}{M_e d} dt = \frac{QE_y}{M_e d} t + C_1 \quad (7)$$

The constant of integration  $C_1$  represents the initial vertical component of velocity at the time the electron enters the electric field between the deflection plates. In the case of the cathode-ray tube, the constant  $C_1$  is zero. When the length of time that the electron remains in the field is substituted from Equation (3), Equation (7) becomes,

$$V_y = \frac{QE_y}{M_e d} \frac{\ell}{V_z} \quad (8)$$

This value of  $V_y$  is now used in Equation (4) to obtain an expression for  $\tan \theta$  in terms of known quantities,

$$\tan \theta = \frac{QE_y \ell}{M_e d V_z^2} \quad (9)$$

In order to determine the distance of deflection  $S$ , one must investigate the vertical displacement of the electron beam  $\delta$  just as it emerges from between the deflection plates as shown in Figure 14 of the enlarged version of this region. The distance  $\delta$  can be determined by integrating Equation (7) with respect to time as follows:

$$\delta = \int V_y dt = \int \frac{QE_y}{M_e d} t dt = \frac{1}{2} \frac{QE_y}{M_e d} t^2 + C_2 \quad (10)$$

The constant  $C_2$  in Equation (10) represents the initial vertical displacement of the electron beam just as it enters the deflection plate region; however, with the choice of axes in this case,  $C_2$  is zero.

When the time  $t = \ell / V_z$  is substituted in Equation (10), the result is

$$\delta = \frac{1}{2} \frac{QE_y \ell^2}{M_e d V_z^2} \quad (11)$$

In the enlarged drawing of the vertical deflection plate region, the distance  $l/2$  is specifically designated so a comparison of the quotient  $\delta \div l/2$  can be made with the terms of  $\tan \theta$  in Equation (9). The quotient of the term  $\delta$  in Equation (11) and the term  $l/2$  results in Equation (12),

$$\frac{\delta}{\frac{1}{2}l} = \frac{\frac{1}{2} (QE_y l^2) / (M_{ed} V_z^2)}{\frac{1}{2} l} = \frac{QE_y l}{M_{ed} V_z^2} \quad (12)$$

which is the same as that given in Equation (9) for the  $\tan \theta$ . The results of Equation (12) indicate that the electron behaves as though it emerged in a straight line from the center of the vertical deflection plate region to the point S on the screen. In this case, the tangent of the angle  $\theta$  can also be found as

$$\tan \theta = S / l_s \quad (13)$$

If the results of Equations (13) and (9) are equated, the factors can be determined which affect the deflection at the cathode-ray tube screen. Upon equating Equations (9) and (13), one obtains

$$\frac{S}{l_s} = \frac{QE_y l}{M_{ed} V_z^2} \quad (14)$$

When Equation (14) is solved for the screen deflection, the result

$$S = \frac{QE_y l l_s}{M_{ed} V_z^2} \quad (15)$$

is obtained. A more simplified expression for the deflection S is obtained when the expression for  $V_z$  in Equation (2) is substituted in Equation (15),

$$S = \frac{QE_y l l_s}{M_{ed} \left[ \frac{2E_a Q}{M_e} \right]} = \frac{E_y l l_s}{2E_a d} \quad (16)$$

Equation (16) is the result required to discuss the deflection characteristics of a cathode-ray tube employing electrostatic deflection. In a given cathode-ray tube application, all the factors of



Equation (16) are constant with the exception of the deflection voltage term  $E_y$ . Thus, the deflection of the electron beam at the face of a cathode-ray tube of this type is a linear function of the deflection voltage. In normal applications the transit-time required for the electron to traverse the deflection plate region is so small in comparison to the period of the deflection frequency that the resulting deflection is proportional to the instantaneous deflection voltage values. A sinusoidal deflection voltage results in a sinusoidal excursion of the electron beam at the face of the cathode-ray tube.

In the case of the horizontal deflection plates, which are located somewhat closer to the screen than the vertical deflection plates, Equation (16) can be used to show that a greater deflection voltage is required to obtain a given deflection at the cathode-ray tube screen. In Equation (16) all terms on the right side can be the same with the exception of  $l_s$ , which must be smaller, and, of course, the symbol  $E_x$ , which must be substituted for  $E_y$ . If the same deflection  $S$  at the screen is obtained, the deflection voltage  $E_x$  must be increased accordingly.

When the cathode-ray tube is employed in direction finding equipment, the gain of the deflection amplifiers is adjusted to compensate for the increased deflection requirements of the horizontal deflection plates. In practice, the amplifier gains are adjusted to produce equal horizontal and vertical deflection on the cathode-ray screen for equal values of antenna input signal.

It should be noted that the motion of the electron beam resulting from one set of deflection plates is perpendicular to that resulting from the other set of deflection plates. As a result of

this action, the instantaneous position of the electron beam on the face of the cathode-ray tube corresponds to the perpendicular vector sum of the respective instantaneous values of the two deflection signals. For example, the simultaneous application of a horizontal deflection voltage, which causes a deflection of four units to the right of the tube axis, and a vertical deflection voltage, which causes a deflection of three units above the tube axis, position the electron beam in the upper right-hand quadrant, a distance of five units from the axis of the cathode-ray tube. This distance represents the hypotenuse of a right triangle whose legs are four unit and three units. When the electron beam is caused to move in a straight-line from the axis of the cathode-ray tube out to the point described in the above example, it is necessary that the deflection voltages vary in such a manner that the vertical and horizontal deflections bear a constant ratio of three to four. If straight-line motion of the electron beam is produced in any given direction on the cathode-ray tube screen, the ratio of vertical and horizontal deflections must be a constant value equal to the tangent of the angle that the beam motion makes with the zero-degree axis.

The fact that this property is required for straight-line deflection is of utmost importance when the cathode-ray tube is used in spheric direction-finding equipment. It means that the spheric must initiate vertical and horizontal deflection voltages that bear a constant instantaneous ratio to one another in such a manner that the oscilloscope presentation is a straight line orientated to correspond to the angular direction from which the spheric originated. That this is automatically accomplished by the combined action of the loop antennas, tuned-frequency receivers, and cathode-ray tube

can be illustrated by considering the results of the foregoing analyses.

The action of the receivers and the cathode-ray tube results in the addition of the respective loop signals at right angles to one another. Thus, the cathode-ray tube presentation can be represented as the perpendicular vector sum of two loops signals. In vector notation, this is

$$E_{ns} + \bar{j} E_{ew} = [E(t)_{sferic} (\cos \theta)] + \bar{j} [E(t)_{sferic} (\sin \theta)] \quad (17)$$

The term  $E(t)_{sferic}$  can be factored from each member on the right side of Equation (17) to obtain

$$E_{ns} + \bar{j} E_{ew} = E(t)_{sferic} [\cos \theta + \bar{j} \sin \theta] \quad (18)$$

The term,  $\cos \theta + \bar{j} \sin \theta$ , is recognized as the vector operator<sup>1</sup> representing a vector which passes through the origin at the angle  $\theta$  with respect to the reference axis.

$E(t)_{sferic}$ , which represents the original sferic radiation, appears in each term of Equation (18) and implies that the horizontal and vertical deflections result from the same time varying signal. Only the magnitude of each differs according to the direction angle  $\theta$ . When the same time-varying signal is applied to both sets of deflection plates, a straight-line presentation results. A given signal naturally bears a constant instantaneous ratio to itself. It must be realized, however, that the two receiver units function to filter out a single frequency component from the complex sferic wave. Any dissimilarity in the receiver units results in deflection voltages that do not bear a constant ratio in presenting a given sferic direction.

The nominal values of the components which compose the respective

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<sup>1</sup>Russell M Kerchner and George F. Corcoran, Alternating Current Circuits (New York, 1950), pp. 65-66.

receiver units are matched as nearly as possible, and certain key components are adjustable over narrow limits to compensate for any discrepancy in the two receiver units. The output from a signal generator can be employed to feed the input terminals of both receivers where the loop signals are normally connected. The result obtained on the face of the cathode-ray tube can be demonstrated by graphical construction. A drawing, called a Lissajous Pattern<sup>2</sup>, is used to plot the cathode-ray tube presentation resulting from the various deflection signals. The Lissajous Pattern is used to illustrate the action of the cathode-ray tube by plotting the respective deflection signals upon a pair of perpendicular axes, and then projecting corresponding instantaneous deflection values to obtain the vector sum deflection which results. Several illustrative examples are shown in Figure 15, where a pure sine wave from a signal generator is employed to produce the deflection signals.

Figure 15 (a) illustrates the straight line presentation which results when identical signals are applied to the respective deflection plates. Figure 15 (b), (c), and (d) represent the oscilloscope display when there is relative phase shift of the sine wave signal in passing through the amplifiers. This phase shift can result from many causes, but normally in matched spheric amplifiers it is caused mainly by the resonant frequency in the two receivers differing by a small amount or slight differences in the "Q" of the respective resonant circuits.

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<sup>2</sup>Herbert J. Reich, p. 634.

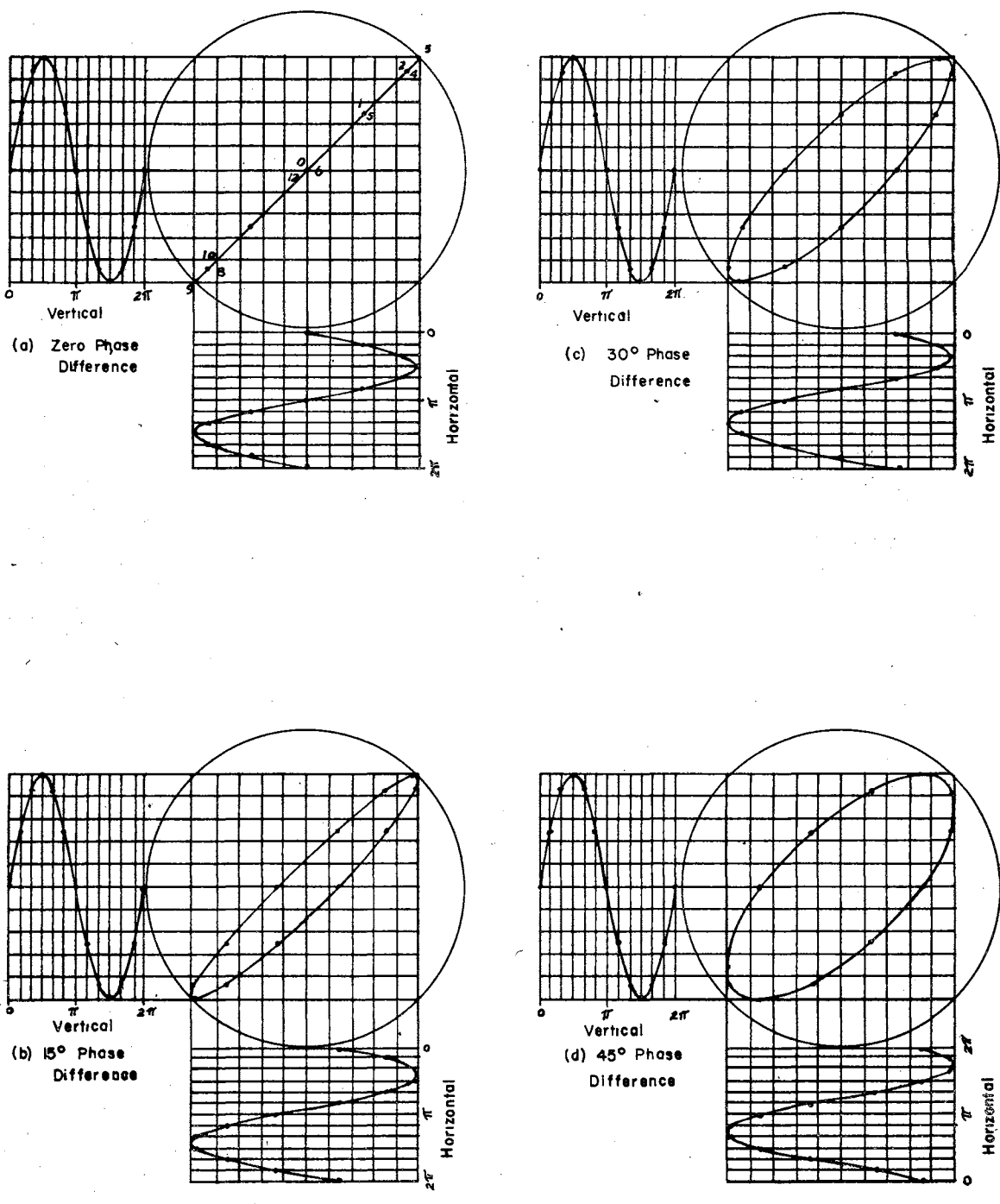


Figure 15. Lissajous patterns resulting from tuning a spheric direction finder using a sine wave signal generator.

When the resonant circuits of the two receivers are identical with respect to frequency and circuit Q and there are no other phase-shift causes in the other amplifier stages, the oscilloscope presentation is similar to that represented in Figure 15 (a), as the oscillator frequency is varied over the entire operating range. The word similar is used in the preceding sentence because the presentation is identical to Figure 15 (b) for the resonant frequency. It is of reduced size, however, for all other frequencies within the operating frequency range because of the shape of the frequency response curve. The receiver is properly tuned when these conditions exist.

Although the preceding requirements of a properly-tuned sferic receiver are easily stated, it requires considerable technical ability to realize them in practice when using only a sine-wave generator to check the alignment. A pulse-tuning technique designed as a standard procedure for the high frequency direction finder, provides a method whereby the tuning requirements can be quickly performed even by unskilled operators. This method has proved to be so satisfactory that it has become the standard tuning procedure on the AN/GRD-1A sferic receivers in use by the United States Air Force.

A short duration pulse is fed simultaneously into both receiver units at the terminals where the loop antennas are normally connected. The pulse shocks each resonant circuit into oscillation at its resonant frequency. The voltage across each resonant circuits has the shape of a damped sinusoidal signal similar to that resulting from the reception of a sferic wave. Under this dynamic test, the resonant frequencies as well as the respective circuit Q can be matched identically.

Figure 16 is drawn to illustrate the type of waveforms experienced when the resonant circuits are shocked by the tuning impulse and to show how an elliptical oscilloscope presentation results when there is a slight time difference in initiating the two waves. The undesirable presentations resulting from spheric action exhibit this elliptical shape. Close investigation of the presentation proves that the pattern does not have the shape of a family of ellipses with a common major axis but rather the shape of an exponential spiral as viewed from an oblique angle. When the problem first became apparent, however, the patterns were results of spheric activity and persisted for such short time intervals that they indeed did look like a family of concentric ellipses. For this reason the term "elliptical presentations" is used to designate them.

With the advent of the high frequency direction finder and the pulse-tuning technique, the "elliptical presentations" could be readily produced and investigated. There are actually three types of elliptical-looking presentations. One appears when the undamped resonant frequencies of the two receivers are identical but the respective damping factors differ; another, when the damping factors are identical but the undamped resonant frequencies of the two receivers differ; and the third, when both the damping factors and the undamped resonant frequencies of the two receivers differ. The damping factor<sup>3</sup> relates to the circuit Q by the following equation:

$$Q = \frac{\omega_0}{2\alpha} \quad (19)$$

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<sup>3</sup>Colin Cherry, Pulses and Transients (New York, 1948), p.25.

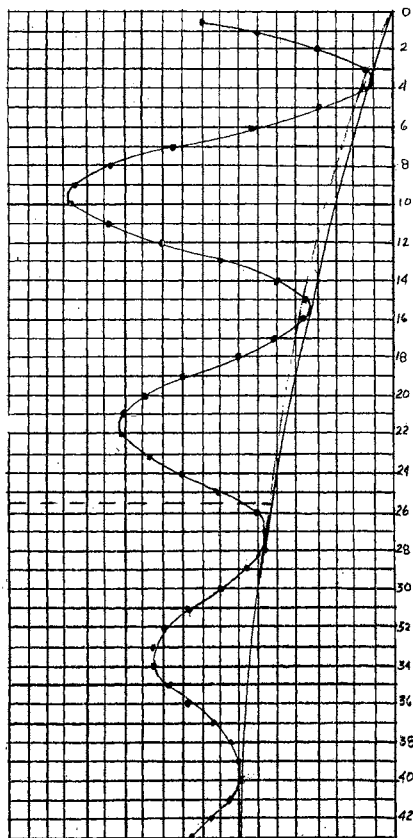
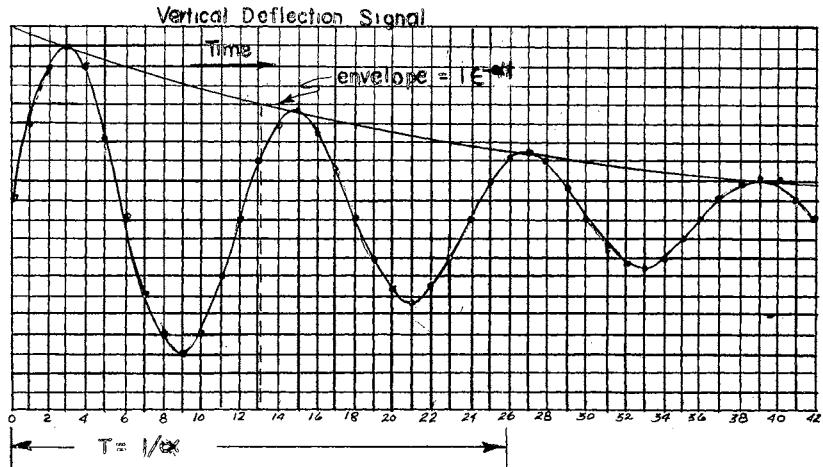
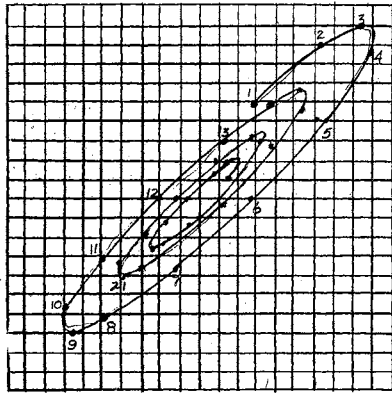


Figure 16. Lissajous pattern illustrating the formation of elliptical presentations due to damped sinusoidal deflection signals that do not commence simultaneously.



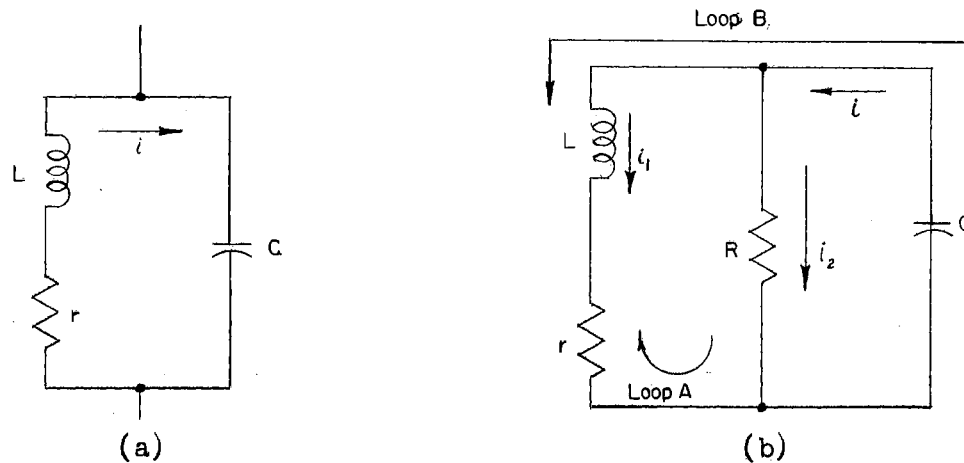


Figure 17. (a). Parallel resonant circuit with losses in the effective resistance of the inductor. (b). Parallel resonant circuit with losses in the effective resistance of the inductor and also in a shunt resistor,  $R$ .

where  $\omega_0$  is the undamped angular frequency and  $\alpha$  is the damping factor. Equation (19) relates to the  $Q$  of a parallel resonant circuit in which there is negligible shunting resistance, the major portion of the losses occurring in the effective resistance  $r$  of the inductance.

The equations relating to the currents and voltages that exist in parallel resonant circuits are necessary in order to thoroughly analyze the problems involved in spheric receivers. Figure 17 illustrates the two cases of parallel resonant circuits, one with additional losses due to a shunt resistance  $R$  and the other with the losses only in the effective resistance of the inductor.

The solution, which is most important in relation to spheric receiver, is the force free solution to the differential equation describing the current which exists in the circuit. In the circuit shown in Figure 17 (a) losses occur only in the effective resistance  $r$  of the inductor  $L$ . The Kirchoff equation around the loop in the positive sense is

$$L \frac{di}{dt} + ri + \frac{1}{C} \int i dt = 0 \quad (20)$$

The solution to Equation (20) is more easily recognized if the integral sign is removed by taking a derivative of the equation and multiplying through by  $1/L$  as follows:

$$\frac{1}{L} \cdot \frac{d}{dt} \left[ L \frac{di}{dt} + ri + \frac{1}{C} \int idt \right] = \frac{d^2i}{dt^2} + \frac{r}{L} \frac{di}{dt} + \frac{1}{LC} i = 0 \quad (21)$$

When operator notation is applied to Equation (21), the solution is the exponential function in which the exponents are the roots to the determinantal equation,

$$m^2 + \frac{r}{L} m + \frac{1}{LC} = 0 \quad (22)$$

The roots of Equation (22) by the quadric equation formula are

$$m = \frac{-\frac{r}{L} \pm \sqrt{\left[\frac{r}{L}\right]^2 - \frac{4}{LC}}}{2} \quad (23)$$

When Equation (23) is rearranged so that the components of the exponential solution can be evaluated, the result is

$$m = -\frac{r}{2L} \pm j \sqrt{\frac{1}{LC} - \left[\frac{r}{2L}\right]^2} \quad (24)$$

The solution to Equation (20) is therefore

$$i = A e^{-\frac{rt}{2L}} \sin(\omega t + \theta) + C_1 \quad (25)$$

The constant of integration represents a d.c. component of current, which may exist in the amplifier associated with the resonant circuit. The amplifiers which are fed by the resonant circuit cannot, however, amplify d. c. Therefore, this term may be neglected. The damped angular frequency is given by the second term of Equation (24) as

$$\omega = \sqrt{\frac{1}{LC} - \left[\frac{r}{2L}\right]^2} \quad (26)$$

The undamped angular frequency of a parallel resonant circuit of this nature is merely,

$$\omega_0 = 1/\sqrt{LC} \quad (27)$$

Therefore, it is seen that the effective inductor resistance  $r$  has made the circuit oscillate at a lower resonant frequency than that of the undamped case.

The effect of the damping term  $e^{-(r/2L)t}$  is the exponential reduction in amplitude of the sinusoidal wave as a function of time. The exponent  $r/2L$  is given the symbol  $\alpha$  and is called the damping factor. In Figure 16, the plot of the damping term is seen to form an envelope that governs the amplitude of the sinusoidal function. The time constant of the resonant circuit is given by

$T = \frac{1}{\alpha} = 2L/r$  and is defined as the length of time required for the envelope of the sinusoidal function to drop to  $1/e$  of its original value as illustrated in Figure 16.

In the case of the resonant circuits employed in spheric direction-finding equipment, the damping factor is quite small and the damped angular frequency is approximately equal to the undamped value

$$\omega \approx \omega_0 = \frac{1}{\sqrt{LC}} \text{ when } \frac{r}{2L} \ll \frac{1}{LC} \quad (28)$$

An adjustable resistance is connected in shunt with each resonant circuit as a matter of convenience in matching the damping factors of the resonant circuits in the two receivers. The two resistors can be manipulated until the desired circuit  $Q$  in each receiver is realized. The nature of the currents involved can be investigated by solving the differential equations for the circuit shown in Figure 17 (b).

The force-free Kirchoff equation around loop B is

$$L \frac{di_1}{dt} + i_1 r + \frac{1}{C} \int i dt = 0 \quad (29)$$

By taking the derivative of Equation (29) and multiplying through by  $1/L$  one obtains

$$\frac{d^2 i_1}{dt^2} + \frac{r}{L} \frac{di_1}{dt} + \frac{1}{LC} i_1 = 0 \quad (30)$$

The force-free Kirchoff equation around loop A is

$$i_2 R - i_1 r - L \frac{di_1}{dt} = 0 \quad (31)$$

The solution of Equation (31) for  $i_2$  results in

$$i_2 = i_1 \frac{r}{R} + \frac{L}{R} \frac{di_1}{dt} \quad (32)$$

It is noted from Figure 17 (b) that  $i = i_1 + i_2$ . When this equation is used with the results of Equation (32), the expression of  $i$  in terms of  $i_1$  results.

$$i = i_1 + i_2 = i_1 + \left[ i_1 \frac{r}{R} + \frac{L}{R} \frac{di_1}{dt} \right] \quad (33)$$

Upon substituting Equation (33) into Equation (30) and collecting terms, one obtains

$$\frac{d^2 i_1}{dt^2} + \left[ \frac{r}{L} + \frac{1}{RC} \right] \frac{di_1}{dt} + \left[ \frac{R+r}{LCR} \right] i_1 = 0 \quad (34)$$

When differential equation operator notation is used Equation (34) becomes

$$\left[ m^2 + \left( \frac{r}{L} + \frac{1}{RC} \right) m + \frac{R+r}{LCR} \right] i_1 = 0 \quad (35)$$

The roots of the determinantal equation are obtained by use of the quadratic equation formula as

$$m = \left\{ - \left[ \frac{r}{L} + \frac{1}{RC} \right] \pm \sqrt{\left[ \frac{r}{L} + \frac{1}{RC} \right]^2 - \frac{4(R+r)}{LCR}} \right\} \div 2 \quad (36)$$

Equation (36) can be re-arranged in order to evaluate the components of the exponential solution as

$$m = - \left[ \frac{r}{2L} + \frac{1}{2RC} \right] \pm j \sqrt{\left[ \frac{R+r}{R} \right] \frac{1}{LC} - \left[ \frac{r}{2L} + \frac{1}{2RC} \right]^2} \quad (37)$$

The solution to Equation (34) therefore becomes

$$i_1 = A e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} \sin(\omega t + \theta) \quad (38)$$

The constant of integration is omitted for the same reason that it is omitted in Equation (25). The damped angular frequency is given by the second term of Equation (37),

$$\omega = \sqrt{\left[\frac{R+r}{R}\right] \frac{1}{LC} - \left[\frac{r}{2L} + \frac{1}{2RC}\right]^2} \quad (39)$$

Under the radical of Equation (39), the coefficient of the  $1/LC$  term is practically unity in practice because the shunt resistor  $R$  is many times larger than the effective inductor resistance  $r$ , and the second term is small compared to the first term. For this reason the damped angular frequency and the undamped angular frequency have approximately the same value, namely  $1/\sqrt{LC}$ .

The damping factor given by the exponent in Equation (38) is

$$\alpha = \frac{r}{2L} + \frac{1}{2RC} \quad (40)$$

as compared with the value of merely  $r/2L$  for the circuit without a shunt resistor. Thus it is seen that the addition of the shunt resistor increases the amount of damping so that a lower circuit  $Q$  results. The resonant circuit time constant has been shortened as seen by Equation (41).

$$T = \frac{1}{\alpha} = \frac{1}{\frac{r}{2L} + \frac{1}{2RC}} \quad (41)$$

In practice, the parallel resonant circuit is the plate load for a pentode type amplifier tube. The Norton<sup>4</sup> constant current equivalent

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<sup>4</sup>Reich, p. 671.

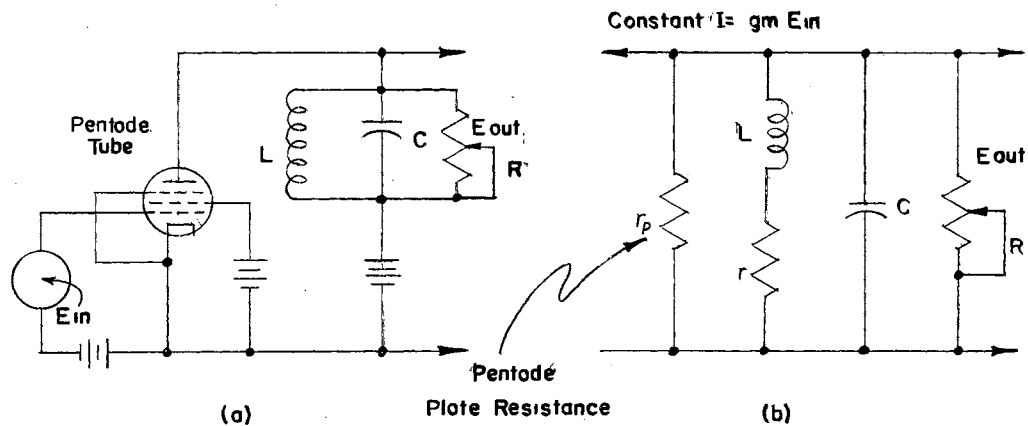


Figure 18. (a). Pentode amplifier used in conjunction with the parallel resonant circuit. (b). Norton constant current equivalent circuit for the circuit (a).

circuit for the pentode amplifier, shown in Figure 18 (b), results in the plate resistance of the pentode tube being in parallel with the resonant circuit as well as the adjustable shunt resistor  $R$ . The plate resistance of the normal pentode amplifier of this type is in the order of one megohm or more. Therefore, the adjustable shunt resistor  $R$  should be small enough to render ineffective any slight variational change in the plate resistance of the pentode tube but large enough not to adversely affect the resonant frequency of the oscillatory circuit. The foregoing result can easily be realized in practice.

It will be noted that Equation (38) represents the current in only the inductive leg of the parallel circuit, but it can be demonstrated that the current existing in the other two legs of the circuit have the same general form. The voltage existing across the parallel combination is the useful output signal, and it can be seen to have the same type wave shape as the inductor current given by Equation (38). The voltage across the parallel combination is obtained by

$$L \frac{di_1}{dt} + i_1 r = V_{out} \quad (42)$$

The substitution of the exponential function for  $i_1$  into Equation (42)

results in

$$\left\{ \left[ \omega L A e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} \right] \cos(\omega t + \theta) \right\} - \left\{ \left[ \left(\frac{r}{2L} + \frac{1}{2RC}\right) L A e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} \right] \sin(\omega t + \theta) \right\} \\ + \left\{ \left[ r A e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} \right] \sin(\omega t + \theta) \right\} = V_{out}. \quad (43)$$

The terms of Equation (43) can be factored and regrouped to obtain an equation of the following form:

$$\left[ K_1 \cos(\omega t + \theta) + K_2 \sin(\omega t + \theta) \right] e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} = V_{out}. \quad (44)$$

The two terms inside the bracket can be combined to give a single sine function as

$$\left[ K_3 \sin(\omega t + \theta_2) \right] e^{-\left(\frac{r}{2L} + \frac{1}{2RC}\right)t} = V_{out}. \quad (45)$$

Equation (45) is of the same form as the equation of the inductor current; the sine term merely has a different amplitude and different phase angle.

The  $Q$  of a resonant circuit<sup>5</sup> can be expressed as its ability to continue oscillating after being shocked by an impulse function. The number of complete oscillations necessary to reach a given ratio  $\rho$  of initial amplitude to final amplitude is given by Equation (46).

$$N = \frac{Q}{\pi} \log_e \rho \quad (46)$$

Thus, for a resonant circuit with a  $Q$  of 19, six cycles are required for the amplitude to decrease to 36.8% of its original value; but for a  $Q$  of 25 eight cycles are required to drop to 36.8% of its original value.

In the case of a spheric direction finder operating at a given

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<sup>5</sup>Estill I. Green, "The Story of  $Q$ ." American Scientist, XXXIII (October, 1955).

frequency, the Q of its resonant circuit gives a quick index to the maximum rate at which the receiver can respond to successive sferics. For example, the Q of the resonant circuit employed in the high frequency direction finder is approximately 20, a fact which means that it requires 30 cycles to decay to 1% of its original value. When the operator has the receiver gain control set to be consistent with the intensity of the storm, the reduction of a sferic presentation to 1% of its initial size allows sufficient recovery in the receiver circuits so that another sferic can be successfully presented. The length of time required for thirty cycles at a frequency of 150 kilocycles (the frequency of the high frequency direction finder) can be found by multiplying 30 times the period of one cycle at this frequency; thus

$$t = 30 T = 30 \cdot \frac{1}{f} = 30 \times \frac{1}{150 \times 10^3} = 200 \text{ microseconds (47)}$$

The result of Equation (47) indicates that a sferic could be presented at a rate of one every 200 microseconds; this corresponds to a frequency rate of 5000 sferics per second. If during the 200 microseconds necessary for presenting a given sferic another sferic occurs at a different angle, an elliptical presentation results. Actually, a given lightning discharge can consist of several strokes in rapid succession over the same ionized path, and the receiver must respond to each of these sferics. The persistency of vision causes the observed presentation of such a multiple stroke to appear as activity at the given angle which fluxuates rapidly in amplitude. The film record, however, shows the individual strokes at the given angle with respective differences in magnitude.

If it is assumed that the same circuit Q can be realized in the resonant circuit of the AN/GRD-1A 10 kilocycle direction finder, then



it can respond to sferics only one-fifteenth as rapidly, approximately 300 sferics per second. This rate seems to be sufficiently high to prevent any difficulty from nearby simultaneous sferics, but in practice maximum theoretical results of an electronic circuit are rarely obtained. Consequently, more trouble is encountered in the AN/GRD-1A low frequency direction finder because of nearby simultaneous strokes occurring at different angular directions than for this same reason in the high frequency direction finder.

In a spheric direction finder it is desirable that the presentation of a given spheric be as rapid as possible, consistent with the amount of light necessary to give a good photographic record. The amount of light issuing from the cathode-ray tube is directly proportional to the length of time that the electron beam maintains the indicated angle. If this length of time is too short, sufficient light is not emitted to produce a satisfactory film record. In fact, the increased rate of presentation for the high frequency direction finder requires a new cathode-ray tube with a higher electron-accelerating potential in order to provide the necessary light output.

#### The Video Amplifiers

In electron-tube amplifiers, the inter-electrode capacitance is the main cause of phase shift at the frequencies utilized in present spheric direction finding equipment. Each amplifier must be capable of handling all the significant frequency components of the pulse-type spheric signal without any adverse effects from tube inter-electrode capacitances.

In order to demonstrate the effects of inter-electrode capacitance,

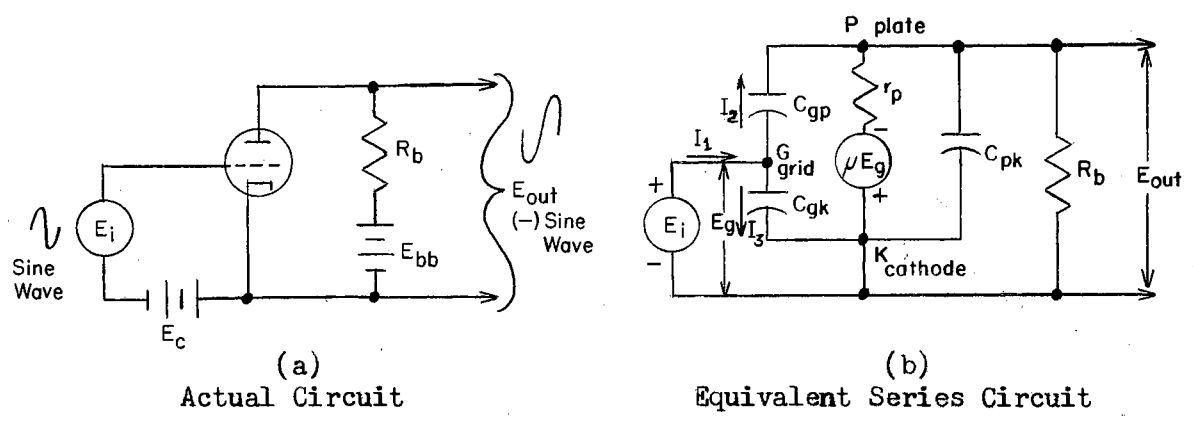


Figure 19. Triode amplifier and equivalent circuit.

a simple triode amplifier shown in Figure 19 (a) will be analyzed.

The series equivalent plate circuit is drawn in Figure 19 (b) with each of the three inter-electrode capacitances connected between the points representing the tube elements. The vacuum tube amplifier has actually four different series equivalent plate circuits. Of these only three apply over particular regions of the frequency spectrum to which the amplifier is capable of responding, but the fourth is a complicated circuit which applies over the entire frequency range of the amplifier. Usually a simple circuit which duplicates the action of the amplifier over the middle range of frequencies is used to determine the general action of the amplifier. For the much higher and much lower frequencies other simple circuits apply which determine how the action of the amplifier deviates from that found in the middle range of frequencies. The equivalent circuits shown in Figure 19 (b) represent that action for the higher range of frequencies, where the effects of the inter-electrode capacitances become prevalent. If the three inter-electrode capacitances are omitted, the circuit becomes one that represents the middle range of frequencies.

In the case of sferic detection equipment, if the higher significant components of frequencies representing the sferic signal even

approach the frequency spectrum where inter-electrode capacitance is the pre-dominant circuit controlling impedance, the result is an intolerable amount of elliptical oscilloscope presentations. This result is usually due to the difficulty of maintaining identical frequency characteristics in the respective amplifier of the two receivers. Therefore, the effects of inter-electrode capacitance are demonstrated at a frequency just high enough so that the amplification of the tube only slightly deviates from that which exists in the middle range of frequencies. The amplification<sup>6</sup> of the circuit shown in Figure 19 (a) for the middle range of frequencies is designated as A and is given by the following equation:

$$A = \frac{E_{\text{out}}}{E_{\text{i}}} = \frac{-\mu R_b}{r + R_b} \quad (48)$$

In Equation (48),  $E_{\text{i}}$  is the input signal,  $E_{\text{out}}$  is the output signal,  $\mu$  is the amplification factor of the tube,  $r_p$  is the dynamic plate resistance of the tube, and  $R_b$  is the plate load resistance of the tube. As is indicated in Equation (48), the amplification does not vary as a function of frequency, a fact which is essentially true throughout the middle range of frequencies.

As the signal frequency increases, the capacitive reactance of the inter-electrode capacitances becomes smaller until a frequency is reached where these capacitances can no longer be neglected in describing the action of the amplifier. The capacitive reactance at a given frequency can be determined by the equation.

$$X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C} \quad (49)$$

The inter-electrode capacitance between the control grid and the cathode, designated as  $C_{gk}$  in Figure 19 (b), appears to electrically

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<sup>6</sup>Herbert J. Reich, p. 144.

shunt the source of the input signal  $E_i$ . The current supplied to it is

$$I_3 = \frac{E_i}{X_{C_{gk}}} = \frac{E_i}{1/j\omega C_{gk}} = jE_i\omega C_{gk} \quad (50)$$

The effective input impedance, represented by the effect of all the inter-electrode capacitances, is found to be

$$Z_{\text{input}} = \frac{E_i}{I_1} \text{ or } \frac{E_g}{I_1} \quad (51)$$

where  $E_g$  is the grid to cathode signal. In this amplifier  $E_i = E_g$ .

$I_3$  is readily determined by Equation (50). When  $I_2$  is determined, the total input current is found to be

$$I_1 = I_2 + I_3 \quad (52)$$

The signal potential across the grid-plate inter-electrode capacitance  $C_{gp}$  is the difference in signal potential between the grid and the plate,

$$E_{gp} = E_g - E_p = E_g - E_o \quad (53)$$

From Equation (48), the plate or output signal can be written as  $E_o = AE_i$ ;

but, since  $E_i = E_g$  in this amplifier, the output signal is also

$$E_o = A E_g \quad (54)$$

Upon substituting Equation (54) into Equation (53), the equation for  $E_{gp}$  is

$$E_{gp} = E_g - A E_g \quad (55)$$

In amplifiers of the above type, the value of  $A$  is negative (Equation 48) in order to account for the inverted signal appearing at the plate relative to that appearing on the grid. Thus, Equation (55) becomes

$$E_{gp} = E_g (1 + |A|) \quad (56)$$

The value of the current  $I_2$  can be found as

$$I_2 = \frac{E_{gp}}{X_{C_{gp}}} = \frac{E_{gp}}{1/j\omega C_{gp}} = jE_{gp}\omega C_{gp} \quad (57)$$

The value of  $E_{gp}$ , as given by Equation (56), is now substituted into Equation (57) to give

$$I_2 = j\omega C_{gp} E_g (1 + |A|) \quad (58)$$

The total current, drawn from the input signal source by the action of the tube and the effects of inter-electrode capacitance, is found by substituting Equations (50) and (58) into Equation (52),

$$I_1 = j\omega E_g [C_{gk} + C_{gp} (1 + |A|)] \quad (59)$$

The value of input impedance  $Z_{input}$  is found by substituting Equation (59) into Equation (51)

$$Z_{input} = \frac{E_g}{I_1} = \frac{1}{j\omega [C_{gk} + C_{gp} (1 + |A|)]} \quad (60)$$

Equation (60) indicates that because of the amplifying properties of the tube the input capacitance to the tube circuit of the type shown in Figure 19 (a) is much larger than the parallel combination of the capacitances involved. The grid-plate capacitance is the largest contributor to the impedance characteristics. Although the plate-cathode capacitance  $C_{pk}$  is not indicated as having any effect on the function of the amplifier, this indication is not strictly correct, for it shunts the output terminals of the amplifier and reduces the amplifier gain at the higher frequencies.

The preceding simplified analysis points out the necessity of employing tubes which exhibit small grid-plate inter-electrode capacitance. For this reason, pentode-type tubes are employed throughout the high frequency spheric receiver. The screen grid acts as a shield between the plate and the control grid, preventing to a great extent the signal coupling between the plate and the control grid.

It should be noted that any appreciable internal impedance of the signal source  $E_i$  in Figure 19(b) allows for the effects of inter-electrode

capacitance to become pronounced at an even lower frequency than predicted by the foregoing analysis.

The value of amplification  $A$  is directly governed by the size of  $R_b$  when a pentode tube is employed. As a result of the constant current action of a pentode, the amplification is most frequently expressed as

$$A = -g_m R_b \quad (61)$$

where,  $g_m$  is the grid-plate transconductance of the pentode tube.

Although a certain amount of overall receiver gain is required to produce a signal of usable magnitude at the oscilloscope deflection plates, it is best to obtain the required amount of gain by use of a number of low-amplification stages in cascade. In this manner, low values of  $R_b$  can be used to reduce the gain of each stage, and in addition reduce the effective internal output impedance of that stage as viewed from the succeeding stage.

Thus, a two-fold benefit is obtained in this manner; an increased input impedance resulting from the lower value of  $A$  and a lower output impedance helping offset the adverse effect of the input impedance of the following stage.

Another type of vacuum-tube amplifier, called a cathode follower, is shown in Figure 20 (a). An analysis of this amplifier indicates that inter-electrode capacitance affects it to a lesser degree than it does the amplifier shown in Figure 19 (a) and that it has a low internal output impedance. Nevertheless, its amplification is less than unity. Although the output signal of the cathode follower is smaller than its input signal, it meets the requirements of a good intermediate stage for purposes of offsetting the undesirable characteristics of the amplifier just described. In this capacity, a

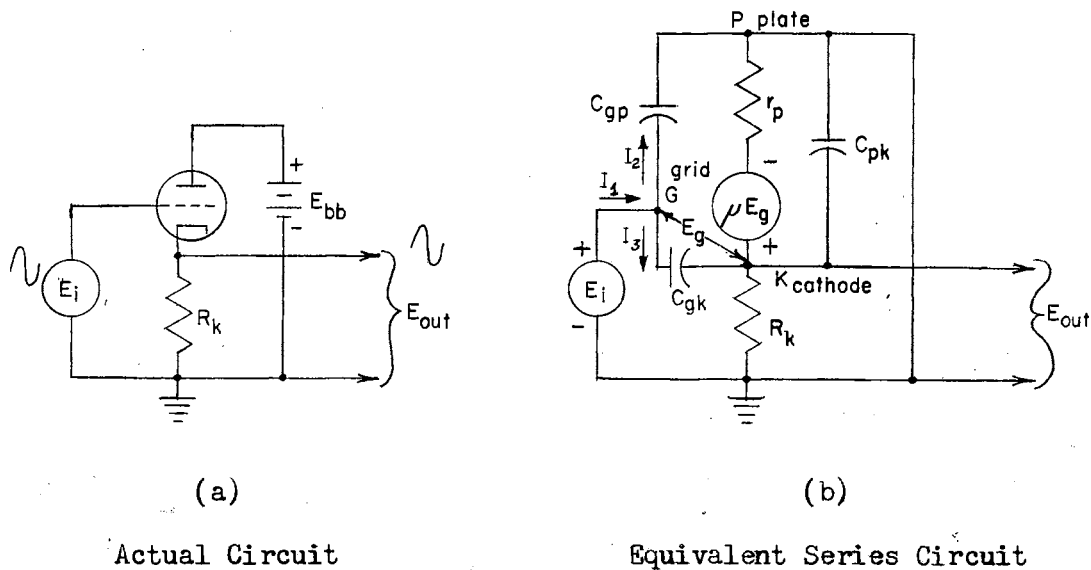


Figure 20. Cathode follower and equivalent circuit.

cathode follower can be used between each pair of the regular pentode amplifiers to extend the high frequency response of the group.

It should be noted in Figure 20 (a) that the cathode follower stage does not invert the signal in the amplifying process. An analysis of the equivalent circuit in Figure 19 (b), reveals that the grid-plate capacitance is directly shunted across the input signal source and appears as its actual value. As a result of the reduced signal voltage across it due to the grid and cathode signal voltages being of the same polarity, the grid-cathode capacitance appears to be a much smaller capacitance than it actually is.

The preceding amplifiers are combined in an attempt to obtain a video amplifier without resorting to compensation methods. Actually, the above arrangement of a cathode-follower stage alternating with a regular amplifier stage was one of the earliest methods used to obtain wide band amplifiers. The practice of compensating the amplifiers with additional reactance elements provides phase shift difficulties which are sometimes hard to control. For this reason, all amplifiers

are designed with pentode tubes employing low-valued plate load resistors to obtain wide-band frequency characteristics without reverting to the use of compensated amplifiers.

The signal from the loop or vertical whip antennas must be amplified before it is fed to the resonant-circuit stage. The sferic signal is complex in shape and composed of many significant frequencies distributed throughout a wide frequency range. Cathode-follower and pentode stages with low-value plate load resistors are therefore employed to provide the necessary signal gain and wide frequency response characteristics.

The sferic signal shocks the resonant-circuit into a series of damped sinusoidal wave trains. It is a well known fact<sup>7</sup> that transient waves can be synthesized from a large number of sinusoidal signals of various frequency values. For an amplifier to faithfully reproduce an amplified version of a transient signal, the amplifier must not discriminate against any frequency of significant amplitude within the synthesized group. Therefore, video type amplifiers must be employed to convey the damped-sinusoidal, resonant-circuit signals on to the deflection plates of the cathode-ray oscilloscope.

The preceding topics will be summarized in order that the overall integration of sferic direction finder operating principles can be obtained.

The output signals from the crossed-loop antenna system contains the information concerning the direction of sferic arrival. The respective loop signals must be amplified and utilized to shock an oscillatory electric circuit into damped oscillations. The amplifiers intervening between the loop antennas and the respective resonant

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<sup>7</sup>Colin Cherry, p. 68.



circuits must not distort the sferic signal. Not only must the resonant circuits oscillate at the same frequency, but each must possess the same decrement associated with the damped sinusoidal wave train. The damped sinusoidal signal resulting across each resonant circuit must be amplified and coupled to the deflection plates of a cathode-ray tube in order to display the angular direction of sferic arrival. The amplifiers between the resonant circuit and the deflection plate system must not discriminate against any of the frequency components composing the transient-type damped sinusoidal wave.

If a single sferic direction finder is employed to determine sferic origin instead of a three-receiver triangulation method, a sense receiver must be employed. The vertical whip antenna feeding the sense receiver must be located in the close proximity of the loop antenna system. The vertical axis of both loops and the sense antennas should coincide. The output of the sense antenna is fed to a receiver which has the same characteristics as the loop antenna receiver units. The output of the sense receiver controls the electron gun of the cathode-ray tube in such a manner that the oscilloscope presentation is an illuminated straight line extending radially outward from the center of the scope face. It is orientated to correspond to the angle of sferic arrival.

#### The High Frequency Direction Finder Block Diagram

A block diagram of the new experimental high frequency direction finder is shown in Figure 21. Certain features that simplify the tuning process are incorporated in order that non-technical personnel can easily tune the unit. The antenna system consists of single-turn crossed

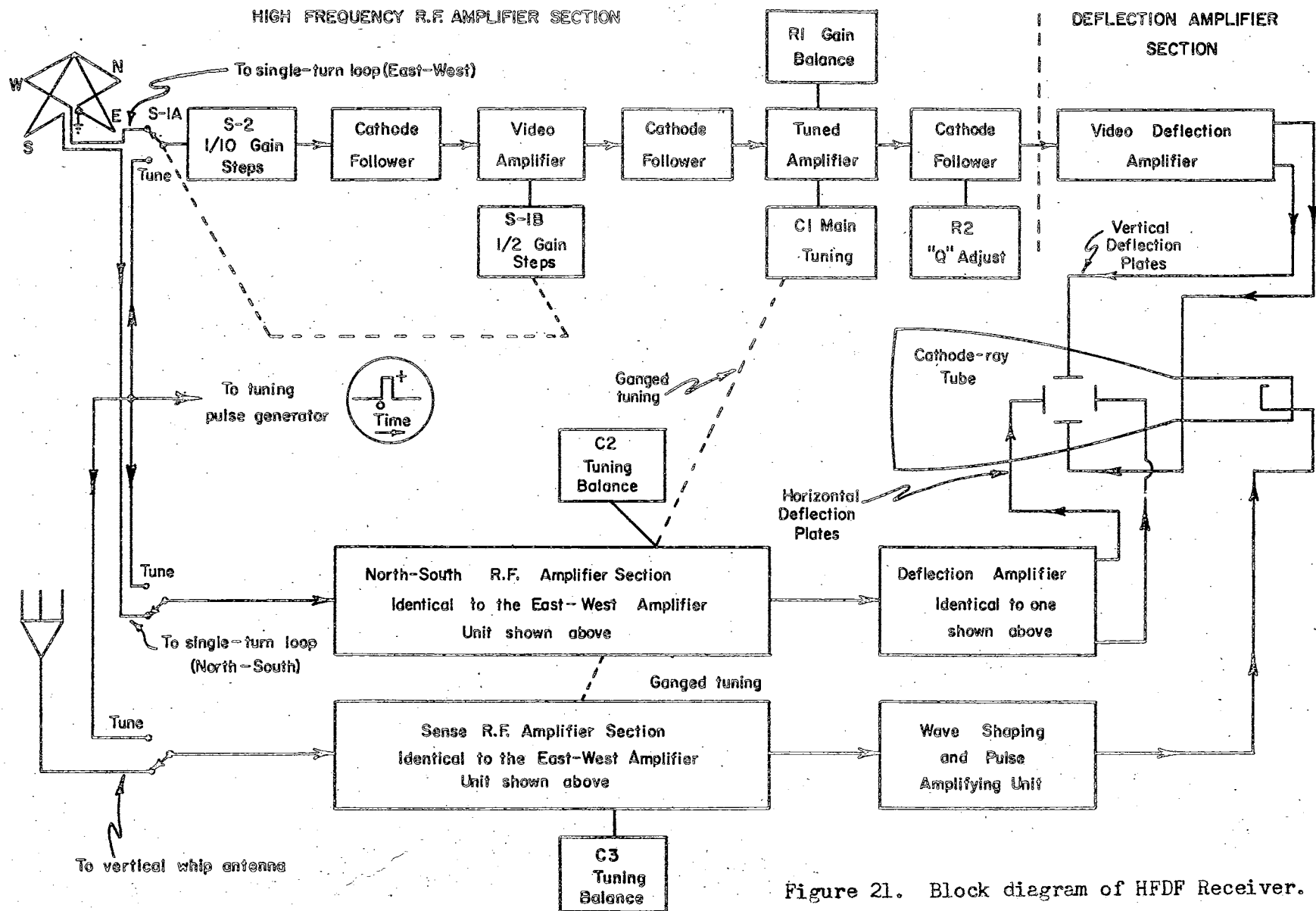


Figure 21. Block diagram of HFDF Receiver.

loops of triangular shape constructed with coaxial cable. A single twenty-two foot mast supports both loops at the center. The base of each loop is forty feet, giving an enclosed loop area of 440 square feet. A vertical coaxial conductor is fastened to the mast and used as the sense antenna. The two single-turn loops as well as the sense antenna are connected into the direction finder as indicated in Figure 21. Three identical receiver units are used for the east-west, north-south, and sense receivers, respectively. Since the three units are identical, the block diagram shows only the stages of one receiver unit in detail.

The output of the single-turn loop is fed from the base of the antenna mast to the amplifier input by way of coaxial cable. The termination of the coaxial cable consists of ten equal resistors in series, with provision that the input to the amplifier may be selected with switch S-2 from any junction point of the ten resistors. This arrangement provides a gain control that varies in increments of one-tenth, called the 1/10-step gain control. The corresponding switch in the other loop amplifier must be set to the same 1/10-step gain position in order to maintain identical conditions in both loop receivers. It would have been convenient to have had a single shaft perform the identical setting in each loop receiver, but this is the pilot model of the receiver and some refinements have not been incorporated.

The percentage of loop signal selected by switch S-2 is coupled to a cathode follower stage to isolate the loop from the first video amplifier stage, and to offset inter-electrode capacitance effects. An additional amplifier gain is provided in the first video stage, giving 1/2-increments to overall spheric loop-amplifier gain. This process is called the 1/2-step gain control.

It should be noted that each amplifier stage in the initial section of the receiver is separated from the next by a cathode follower. This practice is to minimize the effect of input capacitance in producing elliptical scope patterns as discussed previously. Thus, the output of the video amplifier is coupled to the tuned-amplifier stage by a cathode follower.

The tuned-amplifier or resonant-circuit stage is adjustable over a range from 150 kilocycles to 300 kilocycles. The tuning adjustment, condenser  $C_1$ , is ganged to corresponding stages in the other loop receiver and in the sense receiver. The operating frequency is adjustable. Small trimmer condenser adjustments are necessary in the other loop receiver and in the sense receiver. One other adjustment is made in the tuned amplifier stage, the gain-balancing adjustment by means of resistor R-1. This adjustment is necessary in order that equal loop voltages can be made to give equal receiver output signals.

The cathode follower immediately following the tuned amplifier stage is constructed to perform the so-called Q-balance adjustment. The tuned-amplifier stage, when shocked by a lightning discharge, continues to develop a signal for a certain length of time after the lightning has ceased. The oscillatory signal continually decreases in magnitude according to the Q of the tuned circuit. The action is similar to that of a clock pendulum, where friction damps out the swinging motion. In this case, however, the electrical resistance provides the damping action.

If the Q's of both loop tuned amplifiers are not identical, an elliptical pattern is produced. Once the Q-balance adjustment has been made, the instrument will remain in balance for long periods of

time.

A principle based upon the pendulum analogy to the electrical circuit has been used to speed the Q-balance adjustment. The input of each receiver can be disconnected from the respective loop antenna and be connected instead into a pulse generator which couples a rectangular tuning pulse into both receivers simultaneously. This electrical impulse shocks both tuned amplifiers and produces a given cathode-ray tube pattern. The Q-adjust resistor, R2, is manipulated until a straight line is produced on the cathode-ray tube screen, as well as the tuning trimmer on the one tuned amplifier.

If the Q's are not identical, a presentation is produced which resembles an aeroplane propeller (Figure 22). As illustrated in Figure 22, the two damped angular frequencies are identical. This fact is indicated by the passage of all deflections through the origin simultaneously. If the damped angular frequencies differ slightly, the presentation is similar to that shown in Figure 22, with the exception that not all deflections pass through the origin. The leaves of the propeller-type pattern open and form elliptical-looking patterns. In this case, each elliptical-type pattern of the family is smaller than the preceeding and has its major axis rotated from that of the previous ellipse. As can be seen in Figure 22, the difference of Q in the two amplifiers produces succeeding cycles which bear a different ratio to one another than did the previous pair of cycles. As a result of the change in ratio, the pattern demonstrates a slightly different angular presentation for each succeeding cycle. This condition accounts for the gradual angular change of the pattern in Figure 22.

As the Q adjustment approaches balance, the axes of the smaller

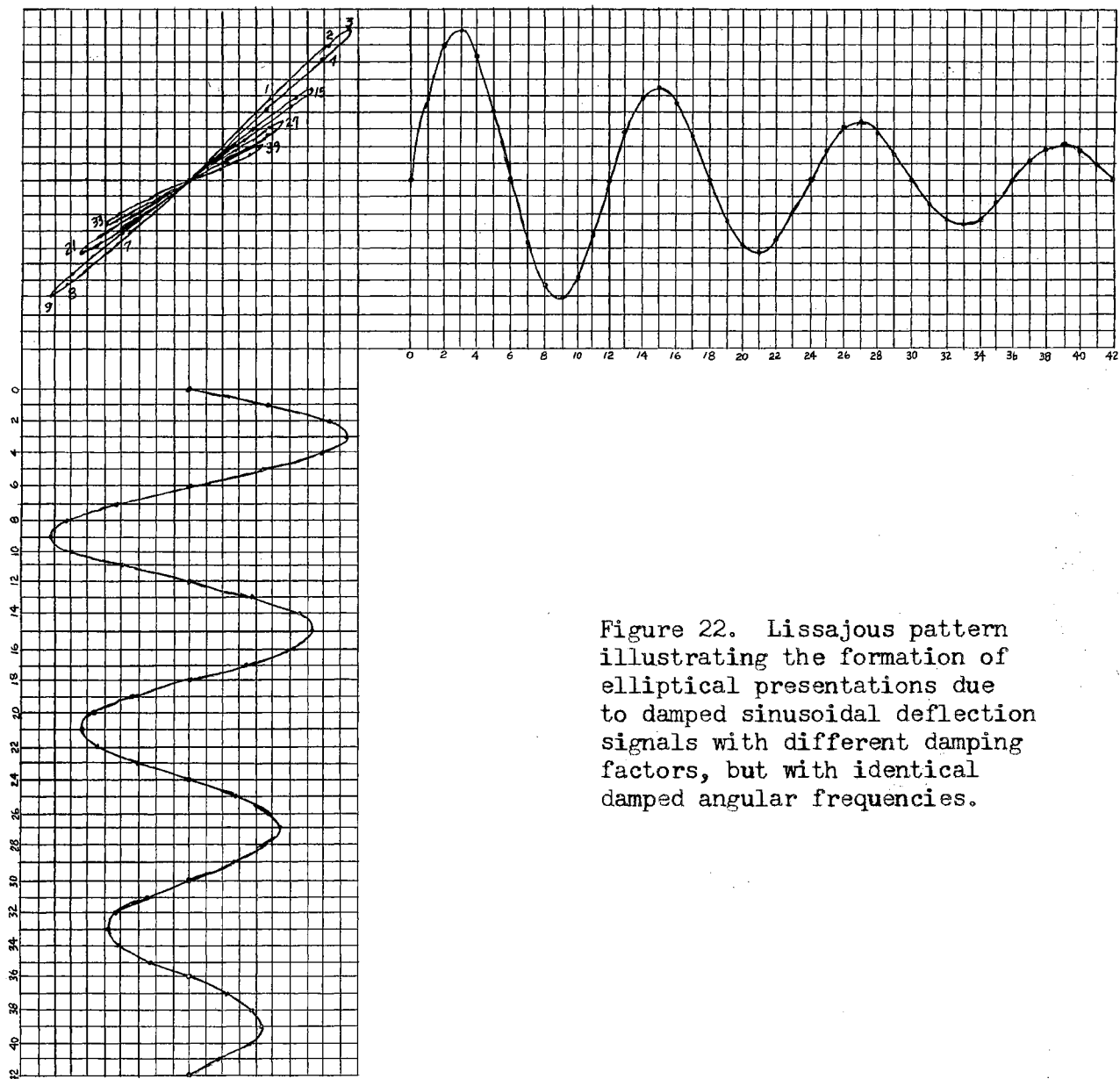


Figure 22. Lissajous pattern illustrating the formation of elliptical presentations due to damped sinusoidal deflection signals with different damping factors, but with identical damped angular frequencies.

ellipses rotate until all are coincident. A pattern of this type is shown in Figure 23. However, the damped angular frequencies differ. When the circuit Q's are identical, as indicated in Figure 23, a straight line can be obtained on the scope if both oscillatory frequencies are made identical by means of the tuning-trimmer adjustment. At this point, it is well to note that the only additional requirements to complete the loop-receiver tuning process are to adjust for gain balance in the two amplifier sections by means of R1 and to adjust the gain controls in each video deflection amplifiers. This action is indicated on the cathode-ray tube when the straight-line presentation occurs in a 45-225 degree direction. Thus, with the respective deflection amplifier set to give equal horizontal and vertical deflection for equal deflection amplifier input signal, R1 is manipulated until the scope pattern occurs on a 45-225 degree slope. The entire tuning process for the loop receiver is then complete.

In order to place the properly-tuned loop amplifier sections into operation, it is necessary only to throw switch S-1 until the loops are again in the circuit. It is necessary to set receiver sensitivity by means of the 1/10-step gain control S-2, and the 1/2-step gain control S-1B to conform with the intensity of the storm. Once the tuning process is properly completed, gain adjustments can be made with the step-gain switches. The tuning process need not be repeated. This gain control procedure was not possible with the original model of the AN/GRD-1A sferic direction finder. It has now been modified to perform in this manner.

In order to prevent overdriving of the amplifiers because of excessive signal strength, the gain of any direction finder should be

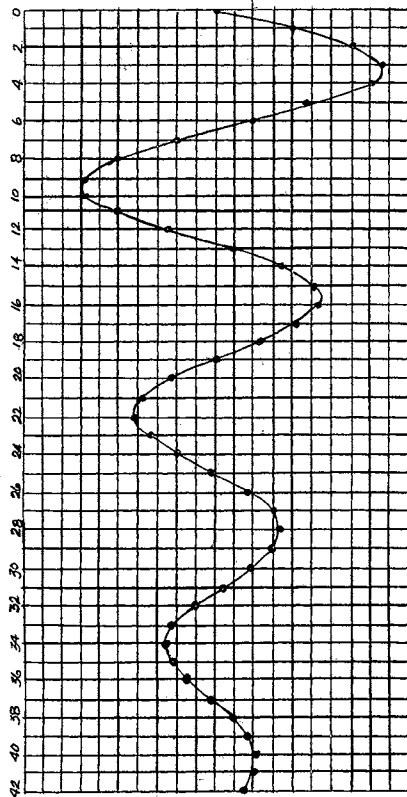
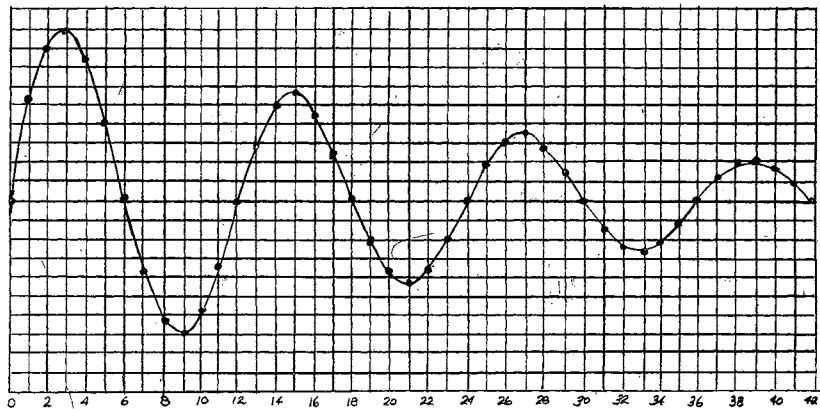
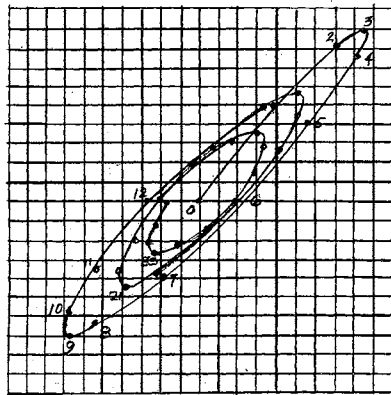


Figure 23. Lissajous pattern illustrating the formation of elliptical presentations due to damped sinusoidal deflection signals with slightly different damped angular frequencies, but with identical damping factors.



reduced as the storm approaches. The overdriving of the amplifier stages can produce serious elliptical presentations as well as deflection voltages that do not bear a constant ratio to the corresponding spheric signal.

### The Deflection Amplifiers

The primary objective of the high frequency direction finder is the angular detection of spherics with as small an amount of elliptical presentations as can be obtained. The initial function of the unit was the photographic recording of these high-frequency directional presentations from the face of the cathode-ray tube for the analysis and the comparison of these records with similar presentations on the AN/GRD-1A low frequency direction finder.

The original cathode-ray tube was of the 5CP11A type with an electron gun potential of -1700 volts and an intensifier potential of +2000 volts. The light emitted by the cathode-ray tube presentation was insufficient to give good photographic records of the 150 KC directional indications from the high frequency direction finder receivers. This difficulty was overcome by employing a type 5RP11A cathode-ray tube with a much higher writing-rate characteristic.

The 5RP11A tube uses an electron gun potential of -1700 volts and a three-band intensifier arrangement, whose potentials are +5000, +10,000, and +15,000 volts, respectively. The additional electron accelerating potential gives more than the necessary amount of light for photographic purposes, but it in turn reduces the deflection sensitivity to such an extent that a much larger deflection voltage must be developed to produce a suitable-sized oscilloscope presentation.

Two deflection amplifiers were modeled after an amplifier designed

by the Western Electric Company for use in their type D151326 oscilloscope. The characteristic of each amplifier is such that essentially constant amplification with negligible phase shift is exhibited throughout the frequency range from 100 cps. to more than 500,000 cps. The original Western Electric deflection amplifiers were compensated to provide high frequency performance in the order of several megacycles per second. In the similar units constructed at the Tornado Laboratory, the compensating coils were omitted to prevent any phase shift problems from existing. The schematic of the vertical deflection amplifier is shown in Figure 3.

As additional technology was developed, the use of the high frequency direction finder was extended to provide for storm intensity evaluation by electronic spheric counting methods and to obtain an instantaneous accurate reading of all the active spheric angles by visually noting such angles from the cathode-ray tube display.

It was discovered that the 5CP11A type cathode-ray tube has entirely satisfactory light-emitting characteristics for the purpose of converting, by means of a photoelectric multiplier type tube, the spheric angular presentation into voltage impulses for counting purposes. In this case, the deflection amplifiers originally designed for this type cathode-ray tube could be utilized in the counter operation. A standard chassis layout was devised for this type deflection amplifier. Six such units were constructed for use in various applications. The output of the high frequency direction finder is fed by coaxial cable lines to a pair of these so-called line amplifiers for each application. The counter oscilloscope employs two of the line amplifiers for deflection purposes. Two other line amplifiers are utilized by the visual

high frequency direction finder oscilloscope. The remaining two amplifiers are maintained as spare units. The schematic of the line amplifier is shown in Figure 24.

The deflection amplifiers use resistance-capacitance coupling. They are also designed to provide equal amplification to a given signal, as the signal frequency is varied over a very wide range. The advantage of the broad frequency response is indicated by the absence of elliptical oscilloscope patterns when the same signal is coupled into each deflection amplifier section, and as the signal frequency is varied over the range from 100 cps to 500,000 cps. The Lissajous Pattern, obtained by using this procedure, is a straight line of constant size. This line indicates that throughout this frequency range there is constant amplification and that there is no appreciable phase difference between the two output signals resulting from amplifier characteristics. This property is the essence for the prevention of elliptical oscilloscope patterns.

#### The Wave-Shaping and Pulse-Amplifying Unit

The output of the sense receiver section must be properly amplified and re-shaped in order to properly execute the function of control in the electron gun of the cathode-ray tube. It is the function of the wave-shaping and pulse-amplifying unit to turn the electron beam on and off in accordance with the demands of the sense antenna signal.

Without the sensing unit, the oscilloscope presentation for a given lightning stroke is a line passing through the origin or zero-signal point, with an inclination proportional to the angle at which



the stroke occurred. It is impossible from merely a photograph of this presentation to tell which azimuth is actually represented by this line. For example, a stroke occurring due east of the direction finder causes a line which points in both the east and the west directions to be presented on the oscilloscope face. If the sense section is employed, the electron beam turns on and off in such a manner that a line which starts at the origin and points only in the east direction is observed.

It is imperative that the tuned amplifier stage in the sense unit have identically the same damped angular frequency and essentially the same circuit Q as the two loop tuned-amplifier stages. If these conditions are not met, the result is incomplete sensing, and the oscilloscope presentation has some indication on both sides of the origin for a given lightning discharge. The portion of the indication which exhibits the greatest magnitude is the direction to the lightning source. The portion on the other side of the origin of smallest magnitude has  $180^\circ$  ambiguity, and because of its presence hinders the analysis of the film data. In spheric direction-finder terminology, the undesired portion of the display which exhibits  $180^\circ$  ambiguity is referred to as "tails" on the desired presentation. In the tuning procedure a straight-line presentation extending out from the origin at an angle of  $225^\circ$  with the complete absence of "tails" in the  $45^\circ$  direction is an indication that all of the receiver sections are functioning properly and are in perfect tune and adjustment. Since all receiver sections are essentially the same, the sense unit can be connected to act as a loop unit for tuning purposes. The initial procedure for obtaining identical operation in all receiver units was the substitution method of comparison. It has been found, however, that by proper

interpretation of the oscilloscope pattern during the tuning procedure a completely satisfactory tuning and adjustment process can be executed. Perfect alignment exists when, in the tuning operation, a straight line extending from the origin out in the  $225^{\circ}$  direction is experienced.

#### The High Frequency Direction Finder Schematic

The circuit diagram illustrating the receiver unit for the high frequency direction finder is shown in Figure 25. The circuit components for both loop receivers and for the sense receiver are essentially identical. A single detailed diagram is used to illustrate the action of all receiver units. In case there is any difference between the respective receiver units, the difference is so indicated on the circuit diagram as well as in the circuit description which follows.

The electrical arrangement of the single-turn, triangular-shaped coaxial loop antenna is illustrated in the upper-left portion of the drawing. The construction of the antenna deserves some discussion as to the method employed so that one man alone can erect such a large structure, and obtain an antenna so nearly aligned in the cardinal directions.

A water tower, which is located 1.4 nautical miles south of the laboratory, can be easily detected on the radar set. It always appeared to be due south of the station. When the water tower was used as a reference point, the north-south base of the antenna was orientated in the exact direction of the water tower dome. Subsequent to the construction of this antenna, a civil engineer determined that the water tower is only south- $00^{\circ}08'00''$ -east of the Tornado Laboratory, making it the best landmark that could have been selected.

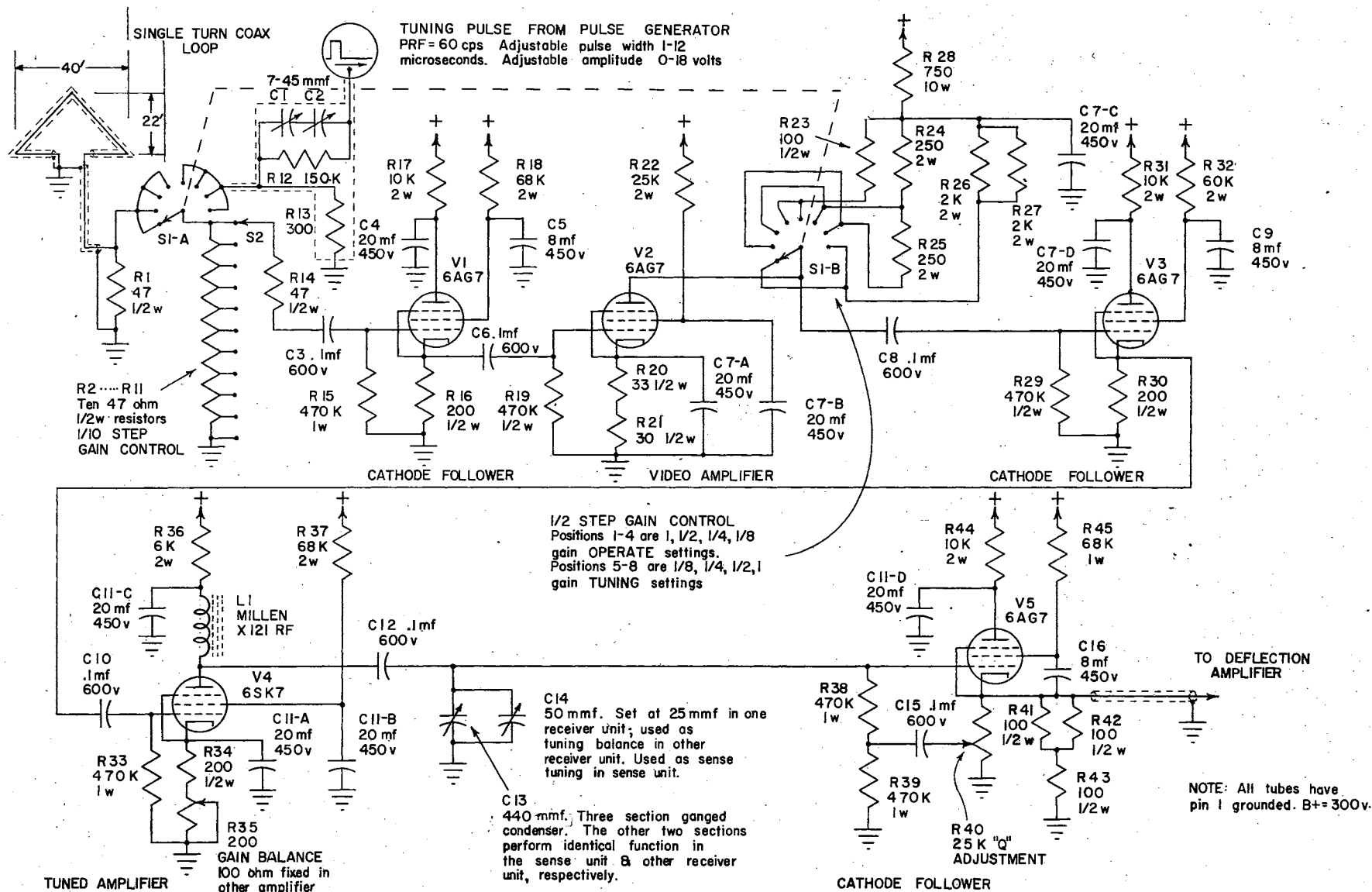


Figure 25. Receiver unit for the High Frequency Direction Finder.

Two wooden posts were set forty feet apart on this north-south base line. At the point midway between the north-south posts the center point of the antenna system was established. In order to determine the east-west axis that passed through this center point, a large right triangle was constructed which employed legs made from two sections of wire 12 feet and 16 feet in length, respectively; and a hypotenuse of a 20-foot length of wire. With the right-angle apex at the centerpoint and the 12-foot leg securely attached to lie along the north-south axis, the 16-foot leg was pulled taut, as well as the 20-foot hypotenuse, until the remaining apex lay along the east-west axis in the easterly direction. This method was repeated for the westerly direction, and the line joining these two east-west points were extended to establish the east and west post positions. After the four cardinal posts were securely in position, a counterpoise was laid to join each post with the midpoint, the ends of the counterpoise wire being securely grounded at each post.

For the next step in erecting the loop antenna system, the length of each piece of coax used for the respective loops was calculated. The distance from the base out to each post, and the distance from each post to the top of the mast was noted. One piece of coax was measured to conform to these measurements and the points carefully noted where the base, posts, and mast top would occur. Another length of coax was carefully matched to this first section and the corresponding support points noted. Five two-by-two inch pieces of lumber were obtained. Each piece was twelve-feet in length. Four of these pieces of lumber were securely bolted to the end of the fifth piece of lumber so that a four legged Eiffel-tower construction resulted (Figure 26).



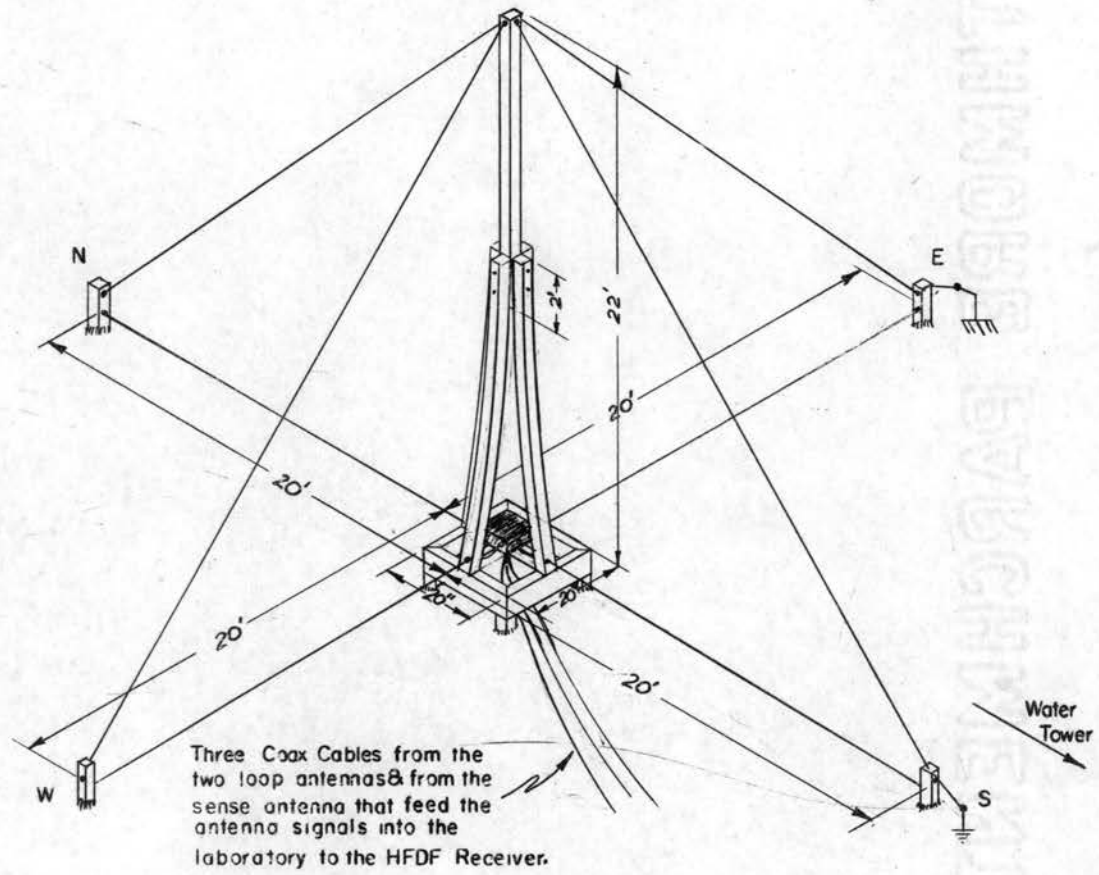


Figure 26. HFDF loop and sense antenna system.

The section where the five lengths of lumber are fastened is two feet in length, making the overall mast approximately twenty-two feet in height. Two equal-length sections of lumber were fastened to the four legs of the arrangement in order to spread the base and provide for a more rigid structure.

A low platform with a level surface was constructed at the center of the antenna system. The platform forms the base to which the mast is securely fastened.

When the mast was in position, a level was used to sight points on the four cardinal posts to which the coaxial cable would be attached. In order to avoid the necessity of having a clamp which might damage the coaxial cable at each cardinal post, a hole was drilled to conform to the exact size of the cable at each post where the cable comes out horizontally from the base of the mast. On the back of each post, just above the first hole, another hole, which inclined toward the top of the mast, was drilled. On the back of each post, the edges of the two holes was filed smooth in order to eliminate the sharp edges. The coaxial cable had to be fed through the two holes extending from the base of the mast, out to the post, and up to the top of the mast.

In order that a single continuous section of coaxial could be used for each loop, the center of each length of coaxial, cut for the respective loops was securely fastened through the holes in the top of the mast. After a single piece of coaxial was fastened to the side of the mast ultimately to form the sense antenna, the mast and all the attached coaxial cables were raised into position and the base of the mast bolted to the base platform.

The four loose ends of the coax were fed through the holes in

the respective cardinal posts and each set to the points previously marked on each coax for the post position. The four ends of the coaxial loops were then fastened through corresponding holes in each of the legs of the antenna mast. They were terminated with chassis-type coaxial receptacles in an antenna junction box, which was situated on the base platform in the region between the four legs of the antenna mast. A pair of equal-length coaxial cables which extended from the Tornado Laboratory also terminated inside the antenna junction box.

It can be seen by referring again to Figure 25 that one end of each loop antenna coax is shorted to the sheath. This connection is also grounded but the other end of the coax has the sheath floating or unconnected. The center conductor is fed by coaxial cable into the receiver unit.

The sheath of the loop coaxial cable connected in such a manner allows it to act as an electrostatic shield for the inner conductor. When an electromagnetic signal is received, both the sheath and the inner conductor have equal induced voltages. The signal in the sheath appears at the ungrounded end and has no effect on the antenna operation; the signal on the inner conductor, on the other hand, is coupled into the receiver unit.

When the particular receiver circuit is employed, the south- and west-ends of the loops are fed into the receivers, while the north- and east-ends of the loop are grounded at the antenna base. When a positive tuning impulse is fed simultaneously into both loop receivers and the sense receiver, connections to the oscilloscope deflection plates are arranged to provide an indication at  $225^\circ$ . When these conditions are properly satisfied, the receiver unit is properly connected

to provide correct spheric incidence presentations. Any deviation from these conditions require that special interpretations be made of the spheric angles indicated.

It is illustrated in Figure 25 that the coaxial cable from the loop antenna is terminated by resistor R1 in parallel with a group of ten resistors comprising the 1/10 step-gain control. Resistor R1 actually is of the proper size to terminate the coaxial cable, while resistors R2 through R11 in series provide little loading of the loop circuit, but merely provide a low impedance voltage divider for the necessary step-gain control. At this point, it should be noted that the top of the 1/10 step-gain control resistors can be disconnected from the antenna by means of switch S1-A, and can be connected instead to the signal from the tuning-pulse generator. It is when switch S1-A is connected to the tuning pulse generator that the receiver resonant circuits are shocked into damped oscillation and the tuning process is performed.

The signal, whether it is the tuning pulse or spheric, is coupled from the arm of switch S-2, the 1/10 step-gain control, into the grid circuit of tube V1. Tube V1 is connected as a cathode follower in order to isolate the antenna from the video amplifier stage V2. The plate load resistor of the video amplifier stage V2 can be changed by means of switch S1-B to adjust the receiver gain to conform with the intensity of the storm. The gain of a pentode tube is directly proportional to the value of its plate load resistor. The sizes of the plate loads allow gain steps of 1, 1/2, 1/4, and 1/8 values. The control switch is called the "1/2 step-gain control." It should be noted that the largest value of load resistor is 1000 ohms, R26 and R27 in parallel. If a small-valued, plate load resistor is chosen, the high frequency response

of the video amplifier stage is adequate to handle the high-frequency components of the complex spheric signal without discrimination. The fact that tube V3, the stage between the video amplifier and the tuned-amplifier stages, is a cathode follower helps further insure adequate high frequency response of the amplifier stages.

The signal appearing at the grid of tube V4, the tuned amplifier stage, is a replica of the signal input to the receiver. Its relative magnitude depends upon the setting of the 1/10 and the 1/2 step-gain controls. The inductor of the resonant circuit is located in the plate circuit of tube V4. Tube V4, a 6SK7 variable-mu pentode, is connected with an adjustable cathode resistor with which to vary the gain of the stage. Resistor R35, the 200-ohm adjustable resistor in the cathode of tube V4, is the gain balance control. The corresponding resistor in the other loop receiver unit has a fixed value of 100 ohms. Thus, if the tubes in the corresponding V4-stages are of similar characteristics, the gain of the one receiver can be adjusted to be greater than, equal to, or less than the gain of the other receiver unit. By means of this adjustment, the two receivers can be set to provide equal output signals to the deflection amplifiers for equal loop antenna signals.

The tuned circuit is of the shunt-fed type so that the main tuning capacitor C13 does not have to be insulated from the chassis. The coupling capacitor C12 prevents the d.c. voltage on the plate of tube V4 from appearing on the tuning-condenser, while electrically connecting the lower end of inductor L1 to the top of the main tuning condenser C13. The lower end of the main tuning condenser is securely grounded. As a result of condenser C11-C, the top of the tuned-circuit inductance L1 is also at ground potential for signals at the parallel

resonant frequency.

The main tuning condenser C13 is one unit of a three-section ganged tuning-condenser; the other two units performing corresponding functions in the other loop receiver and in the sense receiver. Since it is an impractical task to make the capacitance of each section of the main tuning condenser track for the entire tuning range, a more satisfactory solution is obtained by paralleling each section with a small 50 m.m.f. trimmer condenser that can be adjusted to provide identical resonant frequencies in the tuned circuit of the three receiver units. Condenser C14 performs the fine tuning function in the receiver unit shown.

In order to reduce the necessary number of controls appearing on the front panel of the direction finder, the trimmer condenser in the north-south loop receiver is mounted beneath the chassis and permanently set to approximately one-half of its maximum capacitance value. The shaft to the trimmer condenser of the east-west loop receiver is brought through the front panel and manipulated to provide identical resonant frequencies in the two loop receivers. The trimmer tuning condenser of the sense receiver is also controlled from the front panel in order to match the operating frequency in the sense unit to that prevailing in the two loop receivers. Thus, the basic operating frequency of the receiver is selected by means of the main tuning condenser. The two available trimmer condensers are utilized to insure identical operating frequencies in all three receiver units.

As was indicated earlier in this chapter, not only must the resonant frequencies of all receiver units be identical, but also the  $Q$  of all the resonant circuits. The method used in the AN/GRD-1A direction finder consists of a five-megohm potentiometer connected in

parallel with the main tuning condenser.

At the time the high frequency direction finder was being developed, a circuit which required the five-megohm potentiometers would have resulted in an added delay in completing the unit, for no potentiometers of this value were on hand. Again necessity was the mother of invention. A novel application of a cathode follower was used to solve the problem. It can easily be shown that when the grid resistor of a cathode follower is returned to the cathode, its apparent resistance, as far as the input signal is concerned, is increased by an amount inversely proportional to the difference in magnitude between the input signal and the output signal. This fact is demonstrated by calculating the input current as

$$I = \frac{E_{in} - AE_{in}}{R_g} = \frac{E_{in}(1-A)}{R_g}, \text{ and} \quad (61)$$

using this to calculate the apparent input resistance as

$$R_{in} = \frac{E_{in}}{I} = \frac{E_{in} R_g}{E_{in}(1-A)} = \frac{R_g}{1-A} \quad (62)$$

In the above equations,  $A$  is the amplification of the cathode follower stage,  $R_g$  is the actual value of the grid resistor, and  $E_{in}$  is the input signal voltage. The output signal of a cathode follower has the same reference polarity as the input signal but is smaller in magnitude according to the value of amplification  $A$ . Although amplification of the cathode follower is always less than unity, it can be made to approach unity by choosing a large value of cathode resistor. This action increases the gain. On the other hand, it also raises the output impedance which can severely limit the upper frequency limit of the amplifier.

As a compromise, the gain is sacrificed somewhat in order to provide

a low output impedance and thus provide a sufficient high frequency amplifying characteristic. The cathode follower stages shown in Figure 25 provide gains of the order of .6, and exhibit necessary high frequency amplifying characteristics. Thus, it is seen by Equation (62) that the apparent value of  $R_g$  can be made two and one-half times its actual value by simply returning it to a point at cathode signal potential. An adjustable value of apparent input resistance is obtained by returning the signal potential to the grid resistor by means of a potentiometer in the cathode follower output circuit.

The grid of the cathode follower stage V5 as shown in Figure 24 is directly coupled to the main tuning capacitor C13. Two equal value resistors, R38 and R39, are connected in series from the grid to the chassis. At the junction point of the two resistors, a coupling capacitor C15 is connected to feed a portion of the cathode follower output signal from the arm of potentiometer R40 to this junction point. Thus, the potential of the junction point is caused to vary exactly as the potential at the arm of potentiometer R40. The bias voltage of the cathode follower stage is properly maintained although the grid resistor R38 is capable of being electrically connected at the signal frequency to any point along the cathode resistor.

It can be seen that resistor R39 serves as the d.c. path for properly maintaining the bias potential as well as a coupling resistor across which the signal from the arm of potentiometer R40 can be developed. When the arm of potentiometer R40 is manipulated the apparent value of resistor R38 to the input signal from the resonant circuit can be made to vary from its actual value of 470K ohms to approximately 1.2 megohms. The control potentiometer R40, which varies



the apparent resistance shunting the resonant circuit, is called the "Q" adjustment and is used to match identically the circuit Q to that of the other receiver units.

The output of the cathode follower stage V5 is coupled by means of coaxial cable to the input of the respective deflection amplifiers of the visual high frequency direction finder scope and the high frequency direction finder counter scope. In the case of the deflection amplifiers for the oscilloscope which is photographed, the coaxial cables first are coupled to the 90° azimuth rotation device, which re-orientates the oscilloscope presentation in order to keep maximum spheric activity perpendicular to the direction of film travel. Then, from the 90° azimuth rotation device the coaxial cables are connected to the HFDF-WF switchover device, a ten-pole-two-position relay which selects the proper signals for placing the 5RP11 cathode-ray tube in either the waveform or high frequency direction finder mode of operation.

#### The High Frequency Direction-Finder--Waveform Switchover Device

The schematic shown in Figure 27 depicts the basic connections for the high frequency direction-finder--waveform switchover device. In future discussions on the device it will be referred to as merely the HFDF-WF switchover unit.

A ten-pole, two position, rotary stepping relay from war surplus equipment was modified to perform the HFDF-WF switchover operation. The two modes of operation require different deflection signals, different horizontal positioning of the electron beam, different intensity settings, different gating signals, and the energizing and de-energizing of various signal sources whose operation is desired only during one

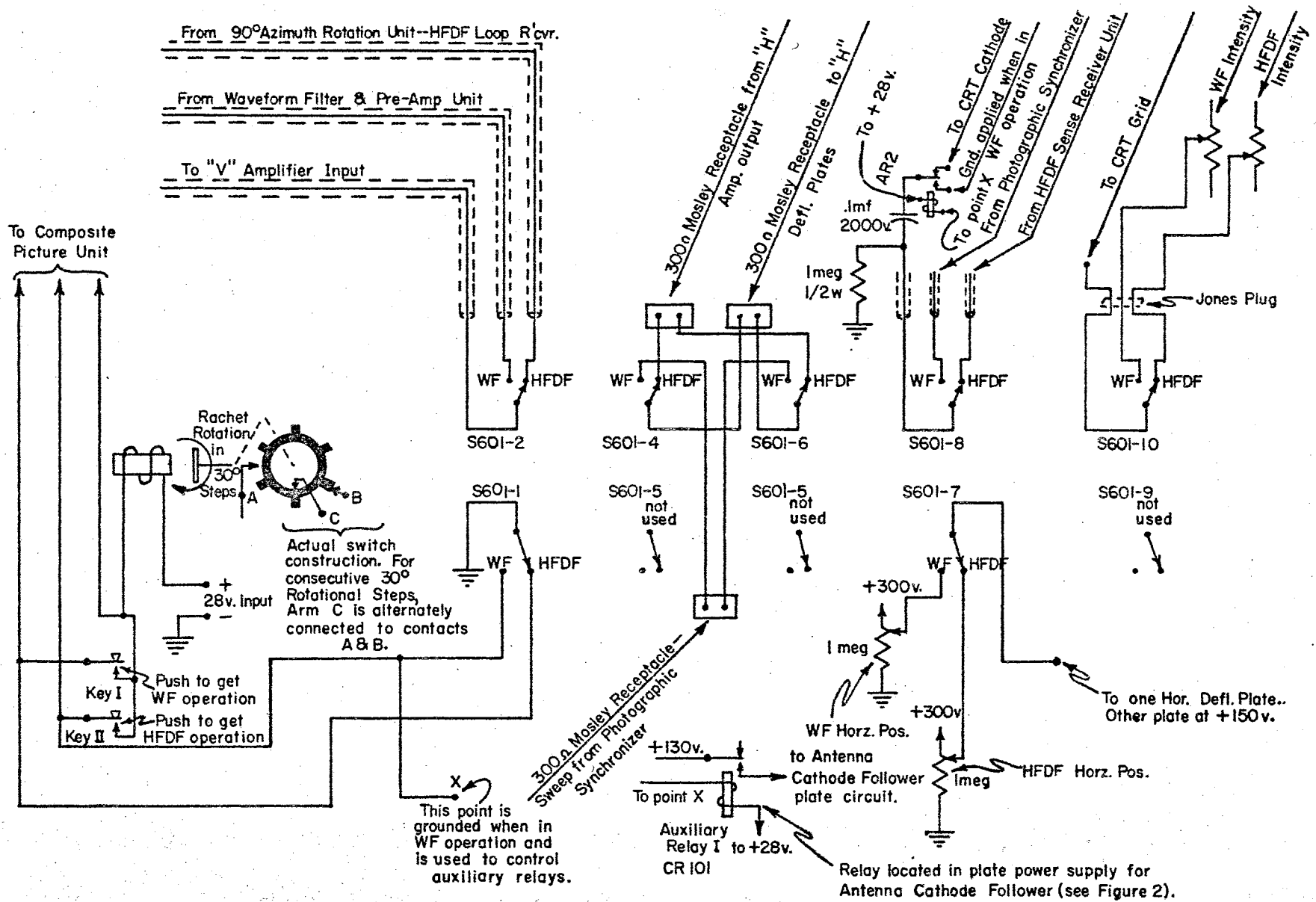


Figure 27. Circuit diagram of the HFDF-WF Switchover Unit.

mode of operation.

A drawing of the actual construction of a switch section is shown in Figure 27; however, symbolic switch symbols are employed to illustrate the circuit connections. The rotating member is advanced thirty degrees each time the rotary relay is energized. For consecutive operations the arm C, which touches the rotating member, alternately makes contact with connections A and B. In symbol form, each of the ten switch sections is designated as a single-pole, two position switch. When the circuit is manually controlled, the operator depresses either Key I or Key II in order to obtain the desired mode of operation.

If Key II is pushed when the switch sections are in the positions indicated in the drawing, no energizing action results because the unit is already in the HFDF position. If Key I is depressed, a complete electrical connection exists through the No. 1 section of the switch and the 28-volt d. c. source is applied to the rotary relay. All switch sections are moved to the waveform contact position. It should be noted that as the relay operates, the No. 1 section of the switch opens the electrical path which applies power to the relay coil. The rotary-type armature has sufficient inertia to insure positive action in operating the switch sections. This feature is important because no continuous flow of relay current is necessary in order to maintain the switch contacts in a given mode of operation.

The No. 2 section of the switch is used to select the proper input signal to the vertical deflection amplifier. In the waveform mode of operation, the vertical signal is received from the output of the waveform-filter and pre-amplifier unit; but, in the high frequency direction finder mode of operation, the vertical signal is

obtained from one of the HFDF loop receivers via the 90° azimuth rotation unit.

The 4th and 6th sections of the switch are used to apply the proper signals to the horizontal deflection plates of the 5RE11 cathode-ray tube. It is necessary to employ two switch sections for this purpose because push-pull deflection signals are used. Short sections of 300-ohm television leads are used to connect the various signals to and from this portion of the switchover unit. In the HFDF mode of operation, the output from the horizontal deflection amplifier is connected to the "H" deflection plates. The input signal to the horizontal deflection amplifier is always from one or the other of the HFDF loop receiver units, depending upon the 90° azimuth rotation unit. In the waveform mode of operation, a push-pull sweep signal is obtained from the photographic synchronizer unit. Switch sections 3 and 5 are not used for fear that electrical coupling, in close proximity to sections 4 and 6, might interfere with the proper functioning of the horizontal deflection signals.

Section 7 of the switch is used to select the proper horizontal positioning voltage for the two modes of operation. The rest position of the electron beam for HFDF operation is at the center of the cathode-ray tube screen; but the beam is positioned at the left side of the screen for waveform operation. The shafts for the two positioning controls are controlled from the front panel of the dual scope unit.

The No. 8 section of the switch is used to select the correct gating signal for the electron gun of the cathode-ray tube. An auxiliary relay is required, for the two gating signals are of opposite polarity and one must be applied to the CRT (cathode-ray tube) grid

whereas the other must be applied to the CRT cathode. The HFDF mode of operation is used the largest percentage of the time. For that reason, all auxiliary relays are connected to be de-energized for this mode of operation and be energized only in the waveform mode of operation. Auxiliary relay AR2 is shown in the de-energized state and connects the negative polarity output of the HFDF sense receiver into the cathode of the cathode-ray tube. If Key I were momentarily depressed, all of the switch sections would move to the waveform position and auxiliary relays AR1 and AR2 would be energized.

The energizing circuit for the auxiliary relays is a result of the dual role performed by the contacts of switch section No. 1. It should be noted that one terminal of each auxiliary relay coil is connected to point "X," the waveform contact of switch section No. 1. The other terminal of the auxiliary relay coil is connected to the positive 28-volt source. Thus, as the arm of switch section No. 1 moves to the waveform position, a ground is applied to point "X" and each auxiliary relay is energized.

If the HFDF-WF switchover device were in the waveform mode of operation, so that auxiliary relay AR2 is energized, the positive polarity gating signal from the sweep generator in the waveform photographic synchronizer is connected to the cathode-ray tube grid circuit. Under these operating conditions a sferic, which initiates a sweep, will simultaneously generate a positive rectangular pulse that is applied by switch section No. 8 to the CRT grid to gate the electron beam for the exact duration of the sweep.

The No. 10 switch section is employed to select the correct cathode-ray tube intensity setting for the two modes of operation.

The intensity, when in the HFDF mode of operation, must be adjusted to provide a small amount of light even in the absence of incoming sferics in order that the axis point of the cathode-ray tube will continually appear on the photographic record. However, in the case of the waveform mode of operation, it is necessary that the intensity be set to a low enough value to prohibit any light except during the actual presentation of a sferic waveform. The two intensity controls are adjusted from the front panel of the dual scope unit. With this arrangement, proper contrast of oscilloscope presentations can be controlled from the camera-end of the light box while viewing the face of the cathode-ray tube through the peep hole provided.

The other auxiliary relay ARL is also energized when the unit is in the waveform mode of operation. This relay functions to connect plate supply voltage to the antenna cathode follower unit only when the waveform operation is desired. By the action of this single relay all signals associated with the presentation of a sferic waveform are disabled when the unit is not in the waveform mode of operation. This procedure prevents the application of any gating, sferic, or sweep signals to the HFDF-WF switchover unit during HFDF operation and thus prevents any difficulty which might arise should these signals be present and couple into the HFDF circuits.

At the left side of Figure 27 is indicated the connection of three wires to the composite picture unit. These three wires are connected to the contacts of Key I and Key II, and, therefore, can be used to remotely control the action of the HFDF-WF switchover unit by duplicating the action of the corresponding control keys. The composite picture unit, which will be discussed in detail in Chapter VI, uses

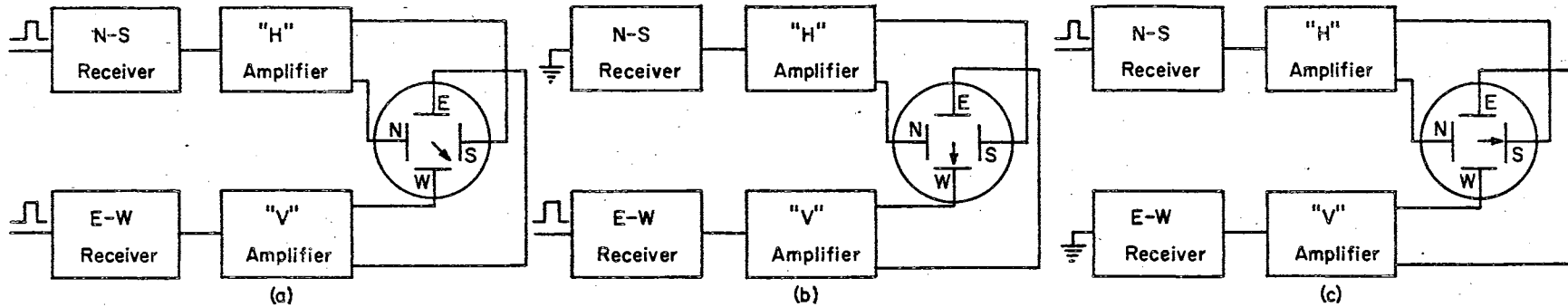
these contacts to automatically control the mode of operation while recording an integrated set of film records.

### The 90° Azimuth Rotation Device

The drawing shown in Figure 28 illustrates the circuit used for controlling the orientation of the cardinal points of the high frequency direction finder presentation on the 5RP11 cathode-ray tube. Before a description of circuit operation is given, it would be profitable to consider the theory related to the requirements for such an azimuth orientation device.

Prior to the development of the 90° azimuth rotation device, the HFDF oscilloscope presentation exhibited north at the left of the cathode-ray tube and east at the top of the tube. A 225°-degree tuning signal exists in the lower right-hand quadrant of the scope as shown in Figure 28 (a). With the tuning pulse applied only to the east-west receiver, the scope presentation indicates due west to be at the bottom of the scope face as indicated in Figure 28 (b). With the tuning pulse applied only to the north-south receiver, the indication is due south at the right side of the scope face as illustrated in Figure 28 (c).

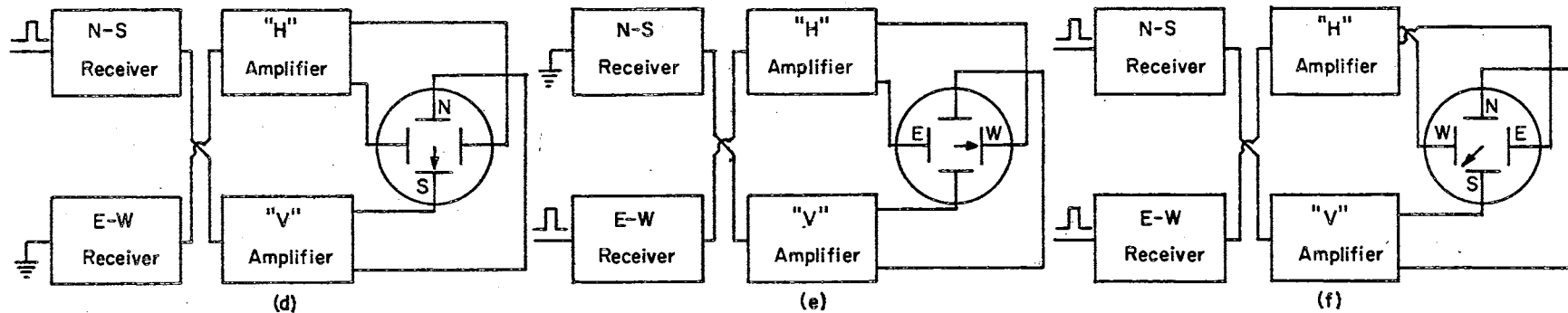
In the design of the 90° azimuth rotation device, it is desired that a simple switching circuit be able to change the HFDF scope presentation to a standard clockwise sequence of the cardinal points, north-east-south-west, with north at the top of the cathode-ray tube. At first glance, it might seem relatively simple to achieve this result by merely changing the connections to the respective deflection plates; but this would involve many difficulties because of the



Normal operation. Identical positive tuning pulse on both receivers is presented at 225°, the lower right-hand corner of the scope face.

Normal operation. Positive tuning pulse on only E - W receiver is presented at 270°, the bottom of the scope face.

Normal operation. Positive tuning pulse on only N - S receiver is presented at 180°, the right side of the scope face.



Amplifier inputs reversed. Positive tuning pulse on only N - S receiver is presented at the bottom of the scope face.

Amplifier inputs reversed. Positive tuning pulse on only E - W receiver is presented at the right side of the scope face.

Amplifier inputs and "H" amplifier output reversed. Identical positive tuning pulse on both receivers is presented at 225°, the lower left-hand corner of the scope face.

Figure 28. Design logic used in the re-orientation of the HFDF azimuth.



different deflection sensitivities of the horizontal and vertical deflection plates. The reversal of connections for azimuth re-orientation must be made where corresponding signals are of equal magnitude. This means that the switching should be performed either at the antenna connections or at the inputs to the deflection amplifiers. Since two other pieces of equipment depend upon the output from the loop receiver units, it is not practical to reverse the antenna connections. Therefore, the most logical point of signal reversal is at the deflection amplifier input connections.

When the amplifier input connections are reversed, a positive tuning pulse applied to the north-south receiver indicates south at the bottom of the scope face. This condition is the desired result as shown in Figure 28 (d). When the positive tuning pulse is applied to the east-west receiver, as illustrated in Figure 28 (e), west is found to exist at the right side of the scope face, just opposite to the desired position necessary to provide a standard clockwise cardinal-point sequence. This undesired condition is easily changed to the desired result by merely reversing the connections to the horizontal deflection plates. A positive tuning pulse is applied simultaneously to both receivers, and the desired result is realized as indicated in Figure 28 (f). Therefore, the 90° azimuth rotation device must interchange the deflection amplifier input connections and also must interchange the leads from the horizontal deflection amplifier to the horizontal deflection plates. In the actual circuit which performs these switching functions, auxiliary relays are provided in order to allow remote control with only impulse-type control signals and to provide a code on the film record to indicate which azimuth position is being

utilized.

The circuit diagram for the 90° azimuth rotation device is shown in Figure 29. Two coax-type relays are employed to perform the interchange of the input connections to the two deflection amplifiers. The coax relays, CR501 and CR502, are provided with auxiliary holding contacts in order to fulfill the requirement of impulse type remote control. It should be noted that with only one of the coax relays energized, the output from one loop receiver is connected into both deflection amplifiers. This condition is employed to balance the two deflection amplifier gains so that with equal input signals, equal cathode-ray tube deflections will be realized.

The circuit connections for the remote control box are shown in the lower part of the drawing. A four-conductor cable connects the remote control box to the main switching unit. The control for selecting the respective azimuth orientation is a three-position, spring-return switch S501. The relays in a de-energized state, as shown, allow for normal operation with north at the left of the cathode-ray tube.

If S501 is pushed momentarily to the right, Relay III is energized and its contacts cause energization of both coax relays as well as the 300-ohm switching relay CR503. The result of this action places north at the top of the HFDF scope face. At the same time coax relays, CR501 and CR502, reverse the input leads to the two deflection amplifiers, relay CR503 reverses the leads to the horizontal deflection plates. A set of holding contacts are provided to maintain these three control relays in the energized state. Since the individual holding contact connections are different, relay CR501 can be placed in an energized state while relay CR502 is left de-energized.

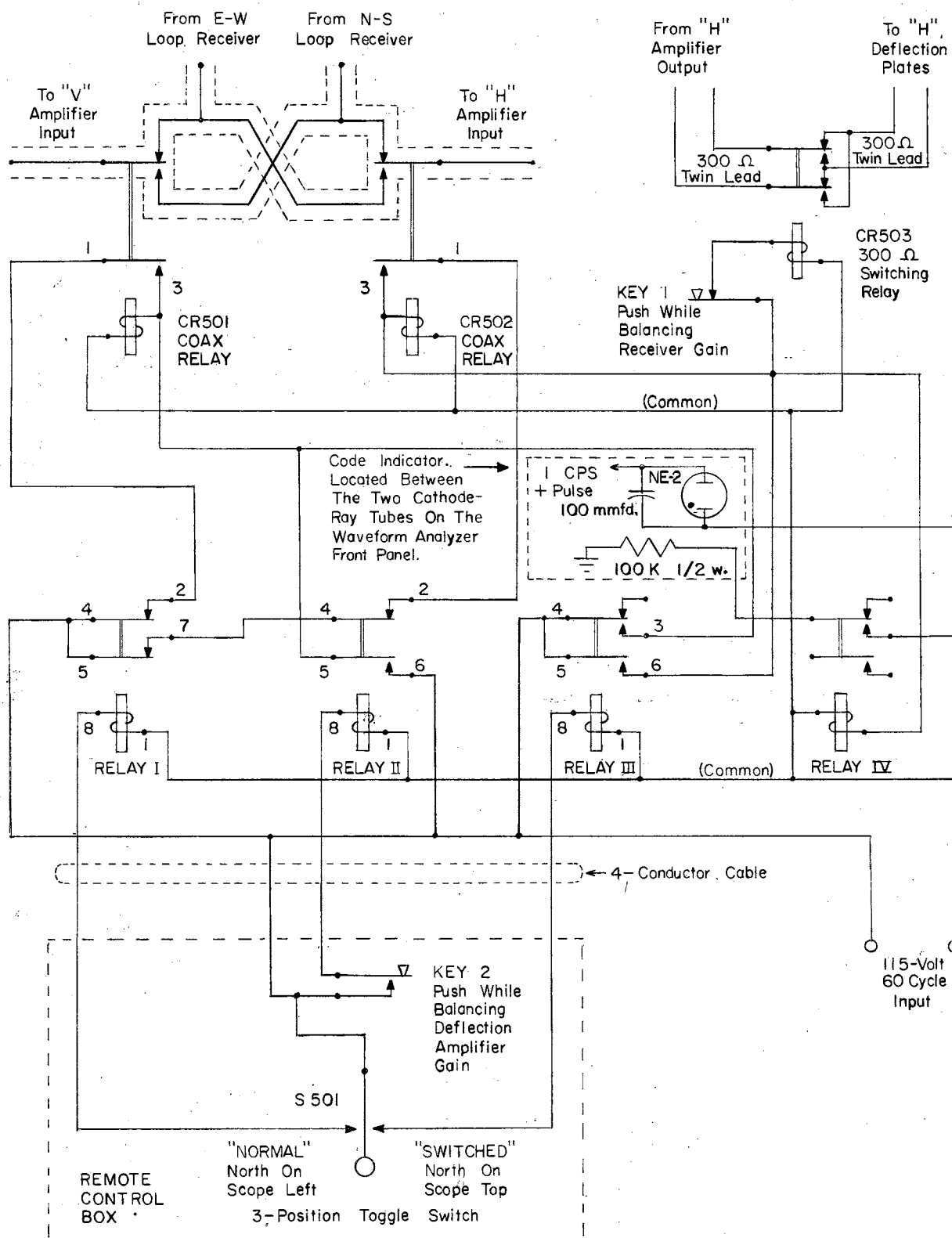


Figure 29. Circuit diagram for the 90°-Azimuth Rotation Device.

The holding contacts of relay CR501 (Contacts 3 and 1) are returned to the a.c. input through the normally-closed contacts 2 and 4 of relay I. On the other hand, the holding contacts of relay CR502 (Contacts 3 and 1) are returned to the a.c. input through normally-closed contacts 2 and 4 of relay II as well as the normally-closed contacts 7 and 5 of relay I. One terminal of each relay coil is connected to the common line of the a.c. input. Thus, if either or both of the coax relays are energized, and it is desirable to return the receivers to the normal operating state, it is necessary only to energize relay I. This action causes both holding-contact return paths to be broken so that all relays revert to their de-energized state. Relay I is energized by momentarily pushing the control switch, S501, to its left position.

The holding contacts of coax relay CR502 perform a triple function. They act as holding contacts for relay CR502, relay CR503, and relay IV. The coils for the three relays are in parallel. When power is applied, all three relays energize, except when Key 1 is depressed to allow relay CR503 to be de-energized individually. The reason for the action of Key 1 will be explained in a subsequent paragraph.

Relay CR502 is energized only when the photographed HFDF scope is to be operated with north at the top. For this reason relay IV, which controls the azimuth-code markings, can be connected in parallel with this relay. Thus, whenever north is at the top of the photographed HFDF scope, the contacts of relay IV energize the neon code-indicator lamp circuit. This lamp is midway between the faces of the two cathode-ray tubes in the dual scope unit. It presents a code mark at one-second intervals on the film record to indicate that north is at the top of the HFDF scope.

The actions of Key 1 and Key 2 can be explained in terms of the desired operating characteristics of the properly-tuned high frequency direction finder. It is necessary that equal cathode-ray-tube deflections be realized when equal-valued signals are applied to the input terminals of the deflection amplifiers. Otherwise, the switching action of the  $90^\circ$  azimuth rotation device causes erroneous angular indications of sferics. It is also necessary that the overall gain of both loop receivers be identically matched for the same reasons.

Referring again to Figure 29, it is evident that by depressing Key 2, relay II energizes. Its contacts 5 and 6 cause coax relay CR501 to energize and hold, but its contacts 2 and 4 cause coax relay CR502 to de-energize. Thus, pressing Key 2 results in all relays de-energizing, with the exception of coax relay CR501. When only the one coax relay is energized, the output from the north-south loop receiver is connected into both deflection amplifier input terminals. If the positive tuning pulse is connected to the north-south receiver input, identical tuning signals result at the input to both deflection amplifiers. Under these conditions, the gain control of one deflection amplifier can be manipulated until equal deflection values are obtained. When this balance exists, the cathode-ray tube indication is a line extending out from the origin in the  $225^\circ$  direction (North is at the left under these conditions and  $225^\circ$  is at the lower right side of the scope face). The control switch S501 is pressed to the left to return the relays to the normal state, and the two receiver units are tuned to have the same operating frequency and circuit Q, so that the oscilloscope presentation is a straight line.

With the relays returned to the normal state, the tuning pulse

indication is at the  $225^{\circ}$  point only if the two receiver gains are identical. The receiver gain balance control, resistor R35 in Figure 25, can be adjusted to bring the indication to the  $225^{\circ}$  position.

Key 1 can be used to advantage in assuring identical receiver gain settings. In Figure 28 (d) and 28 (e) it can be seen that with relay CR503 de-energized by depressing Key 1, the cardinal point sequence is north-west-south-east. The south-west point appears at the lower right side of the scope face. For normal operation with all relays de-energized, the south-west point is at the same position on the oscilloscope face. If both deflection amplifier gains are balanced, depressing Key 1 and operating switch S501 successively from "Normal" to the "Switched" position result in a magnified oscilloscope indication of any unbalance in receiver gain. If there is any unbalance in the two receiver gain settings, the oscilloscope presentation is at the same position for both the "Normal" and "Switched" positions of switch S501. The receiver gain balance control can be further manipulated until the oscilloscope presentation appears at the same location for both switch positions. The operator can then be assured of accurate spheric azimuth indications regardless of whether north is at the left or at the top of the oscilloscope face.

#### The High-Frequency Direction Finder Sense Wave-Shaping Circuit

The sense wave-shaping circuit (Figure 30) functions to gate the electron beam of the cathode-ray tube to provide a single azimuth indication for each spheric. As was pointed out earlier in the chapter, the oscilloscope presentation with loop receivers alone is a line extending across the face of the tube on both sides of the origin

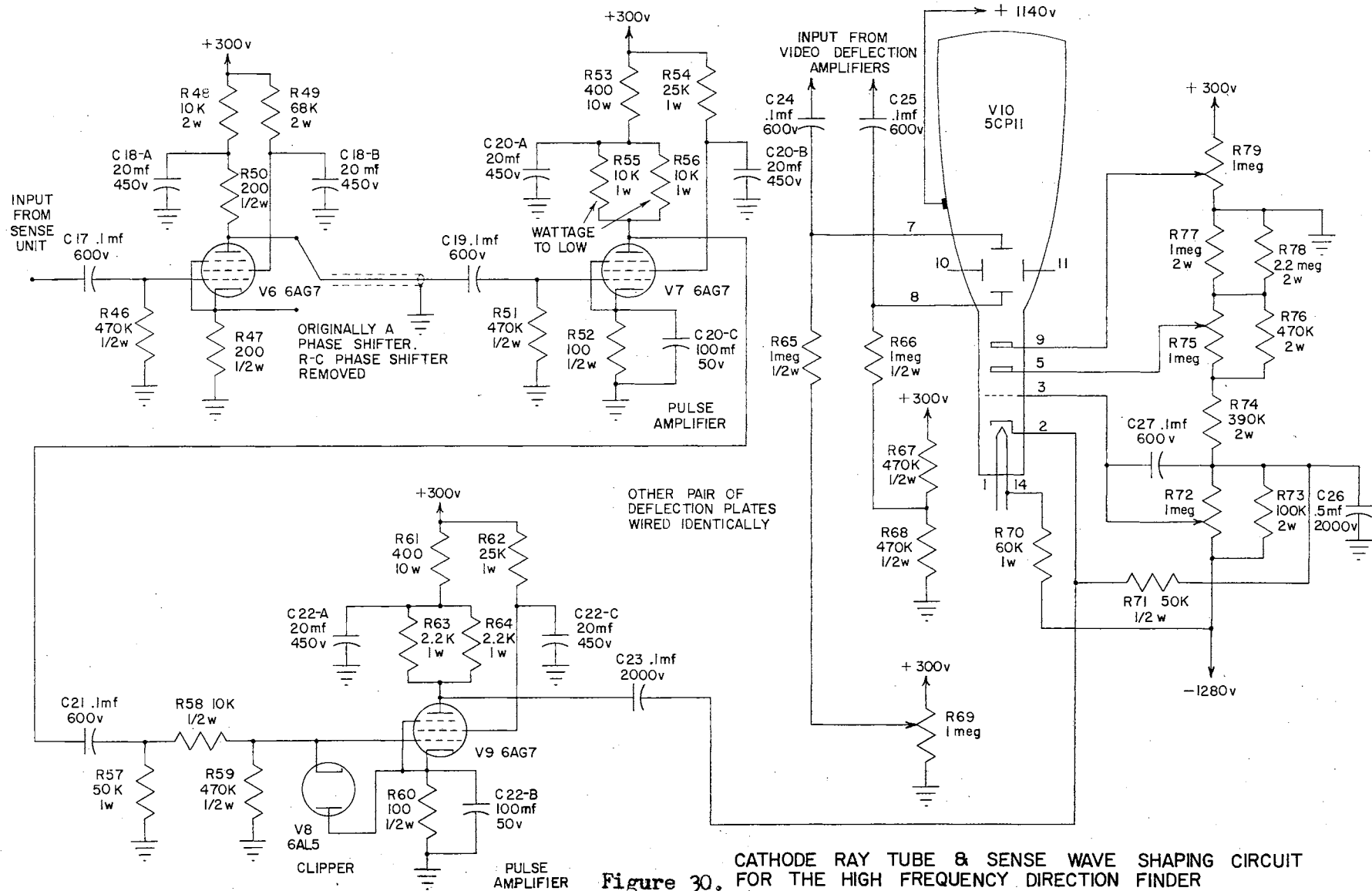


Figure 30. CATHODE RAY TUBE & SENSE WAVE SHAPING CIRCUIT FOR THE HIGH FREQUENCY DIRECTION FINDER

indicating both the correct azimuth and its opposite, which is  $180^\circ$  in error. The sense receiver unit, however, produces a signal, which when properly amplified and shaped, can control the electron beam of the cathode-ray tube so that only the correct azimuth is presented on the face of the tube. It is the purpose of the circuit shown in Figure 30 to take the signal from the sense receiver, properly shape it, and apply the reshaped signal to the cathode of the cathode-ray tube in order to turn on the electron beam at the proper times.

The damped sinusoidal signal, resulting from spheric reception by the sense receiver, is coupled into the grid of tube V6. Tubes V6, V7, V8, and V9 serve merely to amplify this damped sinusoidal wave train and, by clipping action, change the first 30 or so cycles into a nearly rectangular shape. The polarity of the signal applied to the cathode of the electron gun is negative on the half-cycles that correspond to the desired azimuth indication and positive on the half-cycles that correspond to  $180^\circ$  ambiguity. This action results in a single correct azimuth indication for each spheric presented on the oscilloscope.



## CHAPTER V

### The HFDF Counter

As stated in Chapter I, the Signal Corps laboratories had developed a counter for use in conjunction with the AN/GRD-1A direction finder. When the AN/GRD-1A was modified to reduce its elliptical presentation tendencies, the light output from the cathode-ray tube was insufficient to provide satisfactory operation. Prior to this time, some discussion had been made concerning the possibility of using such a counter in conjunction with the high frequency direction finder (HFDF). It was already evident that the HFDF presentation was not plagued with elliptical patterns nearly so much as was its companion, the AN/GRD-1A. Thus, work was begun on the design and development of an HFDF counter that would function along the same principles as did the AN/GRD-1A counter.

Many improvements to render the functioning of the counter automatic were incorporated. Since the Signal Corps counter does not have a fixed scanning period, the correlation of records and time are difficult. The HFDF counter uses a synchronously controlled servo-driven scanner which eliminates the correlation difficulty. The Signal Corps counter has a mask-type slit that scans directly in front of the cathode-ray-tube face, but the HFDF counter uses a lens-projection system to eliminate parallax and to increase the angular resolution. The HFDF counter also employs a pen-drive servo unit to record the spheric count on a moving paper tape. Azimuth markings are automatically placed along the border of the tape to make the reading of the data an easier

task. In fact, once the HFDF counter is placed in operation, it functions automatically in providing a permanent record of storm intensity as a function of time and azimuth.

#### The HFDF-Counter Scanner

A drawing of the HFDF scanner unit is shown in Figure 31. The HFDF presentation appearing on the face of the 5CP11-cathode-ray tube is focused by means of a single lens, and the image position corresponds to the plane of the scanning slit. The scanning slit, which rotates one-degree per second, consists of two Gillette thin razor blades situated in the image plane, with their sharp edges forming a radial slit whose width is equal to the thickness of one razor blade. An adjustable aluminum mask allows only a small length of the slit to be active. The mask can be moved radially to allow the active portion, through which light can pass, to be situated any distance a maximum of  $7/16$  inch from the axis of slit rotation. Thus, a spheric presentation must coincide with the angular position of the slit and also be of sufficient amplitude to produce any light which passes through the active portion of the slit and reaches the counter photocell.

It was found that the image of a spheric presentation does not produce any light ray parallel to the axis from points off the axis, if such points are further from the axis than the radius of the projecting lens. This fact was observed experimentally and subsequently proved graphically by the ray-method of determining image size and position. For this reason, a pair of prisms are used to bring the diverging light rays more in line with the axis of the slit system. The light emerging from the second prism is focused on the cathode of a 931-A

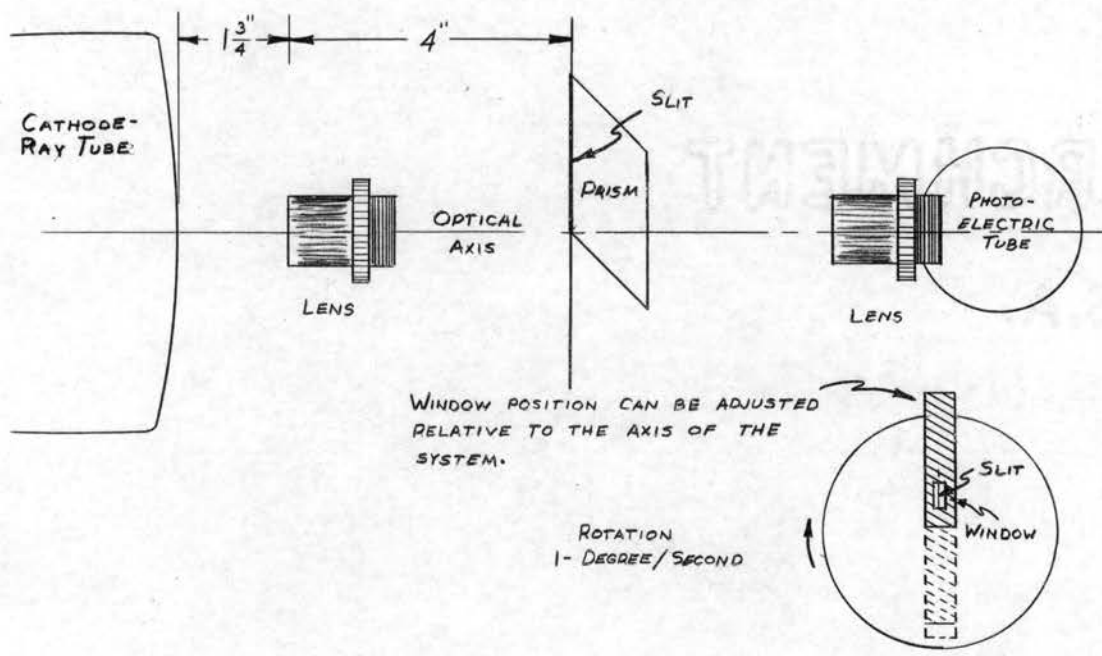


Figure 31. HFDF Counter Scanner.

photoelectric multiplier tube. The radial slit is mounted on a gear in such a manner that the slit can be rotated about the axis of the lens system. The gear is mounted on a large ball-bearing assembly, the center of which has been removed to allow the optical system to pass light through to the photo-cell unit. The gear upon which the slit is mounted is driven by a servo motor at one-degree per second (one-sixth revolution per minute).

Because the slit-drive servo motor is synchronously controlled by a clock motor, the position of the slit is accurately known for each instant of time once the drive system has been synchronized with the time signals from the Bureau of Standards radio station WWV. The slit-drive servo motor and its control circuits will be discussed in a subsequent topic of this chapter.

#### The HFDF Electronic Counter Unit

As pointed out in Chapter I, an electronic counter was developed in the summer of 1952 and called the strep-rate meter (stroke-repetition-rate meter). The unit was never put into operation because the Signal Corps sent the sferics azimuth incidence integrator for use at that time. Thus, when the HFDF counter was developed, the electronic counter, which could convert the light impulses presented by the cathode-ray tube into a d.c. voltage, was already available. The electronic counter needed only minor circuit modifications to perform the electronic counter function in the new system.

The schematic for the electronic counter is shown in Figure 32. As the scanner slit passes an active azimuth angle, light from the HFDF presentation at this angle passes through the optical system and arrives

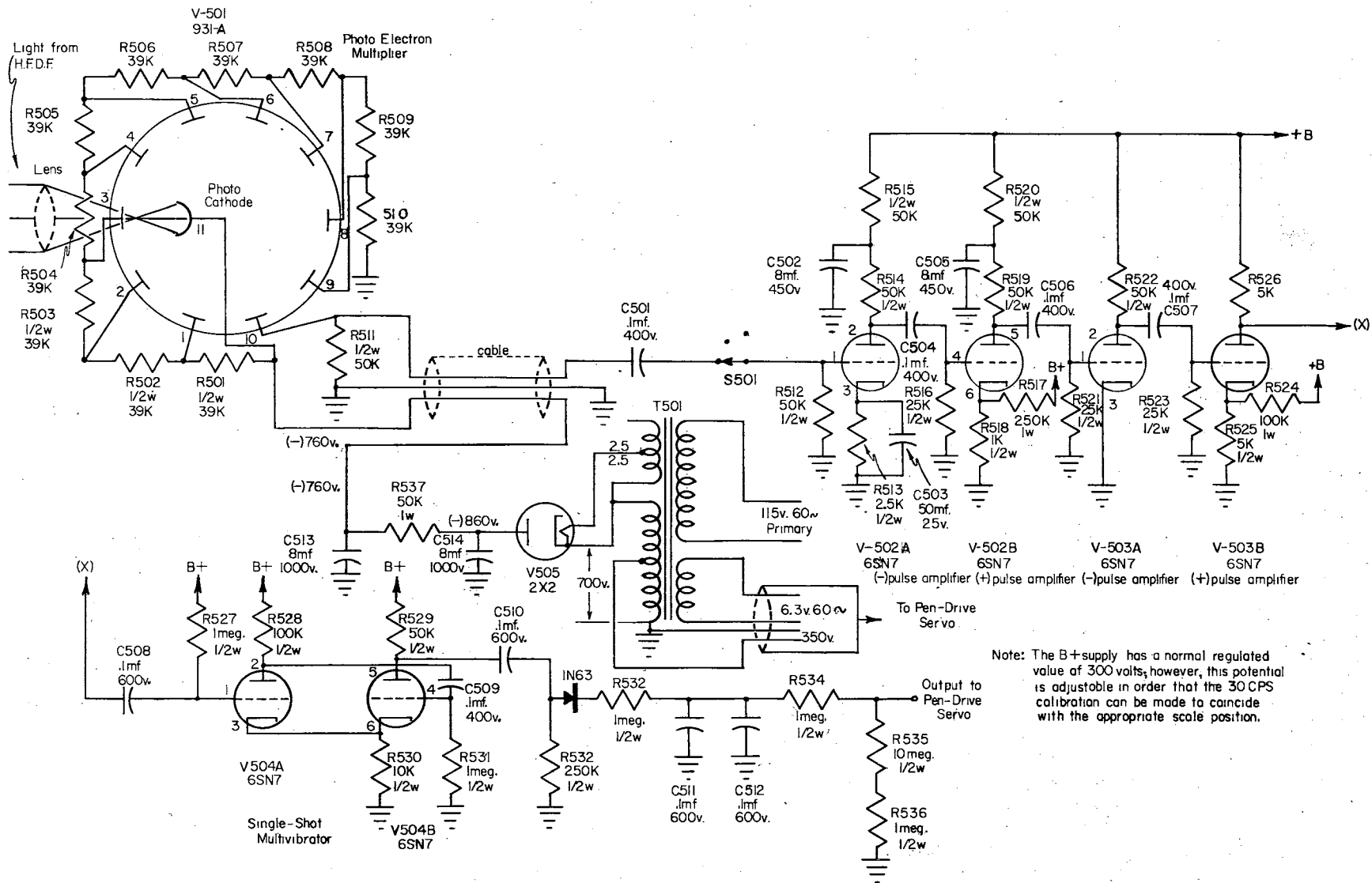


Figure 32. The HFDF Electronic Counter circuit diagram.

at the photocathode of tube V501. Tube V501, a photo-multiplier tube<sup>1</sup> with approximately 76 volts between successive dynodes, converts the spheric light-impulse into a negative-polarity voltage impulse. The negative voltage impulse, which appears across R511 in the anode circuit, is coupled by condenser C501 into the first amplifier stage V502A. The high potential, which is necessary in the operation of photomultiplier circuits, is designed to be of negative polarity with respect to the chassis. With this arrangement only one high voltage cable is required and the output coupling capacitor C501 can have a low voltage rating.

The first few amplifier tubes serve not merely to amplify the output of the photomultiplier but also to reject noise and sixty-cycle interference. The output of the last amplifier stage, tube V503B, triggers a one-shot multivibrator. The one-shot multivibrator, consisting of tube V504A and tube V504B, produces a rectangular pulse for each spheric viewed by the photomultiplier tube. This method produces a rectangular pulse which is independent of the spheric amplitude. The magnitude of the rectangular pulse, however, is dependent upon the value of plate supply voltage. This fact is utilized in establishing a particular output signal for a given spheric repetition rate.

The rectangular pulse output from the multivibrator is fed to a crystal diode rectifier, which produces a d. c. output that is proportional to the repetition rate of the spheric impulses. A filter circuit, consisting of resistors R533, R534, R535, and R536 plus condensers C511 and C512, serves to produce a more constant d. c. output for the low spheric repetition rates experiences.

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<sup>1</sup>George E. Happell and Wilfred M. Hesselberth, Engineering Electronics (New York, Toronto, and London, 1953), pp. 458-459.

The original detector circuit employed a diode-tube rectifier and fed the d.c. output to a vacuum-tube voltmeter that served as an indicator. Variation in the diode tube characteristics made the circuit undesirable for use in the present unit. For that reason, the crystal diode was substituted for the vacuum tube in the performance of the detector function.

The output of the counter consists of a d.c. voltage whose magnitude is proportional to the number of sferics per second which are viewed by the photo-multiplier tube. The masking action of the rotating scanner slit causes the voltage also to be a function of azimuth. The scanning slit rotates at a constant angular velocity of one-degree per second. When the electronic counter voltage is recorded on a paper tape which moves at a constant velocity, a record is obtained which represents storm intensity as a function of azimuth and time. The next topics deal with the equipment required to convert the feeble counter voltage into pen positioning power necessary to produce the permanent tape record, and the equipment needed to synchronously drive the scanning slit at a constant angular velocity.

#### The Pen-Drive Servomechanism

A certain amount of power is required to position the recording pen in accordance with the demands of the output voltage from the electronic counter. To supply this power, a fast-acting servomechanism is employed. Commercial equipment, which exhibits the required characteristics, costs about \$645. The pen-drive servo presently in use at the laboratory was constructed from surplus aircraft radio direction finder components for a fraction of this cost.

The schematic for the laboratory-constructed, pen-drive servomechanism is shown in Figure 33. The unit functions to compare the voltage obtained from a linear potentiometer against the voltage output from the electronic counter. When any difference between the two compared potentials exists, a servo motor operates to move the potentiometer arm until the difference is zero. By means of a pulley and cord mechanism, a recording pen is caused to move in a linear manner, according to the position of the potentiometer arm. Thus, the pen marking will be directly proportional to the voltage received from the electronic counter.

A sixty-cycle synchronous converter, commonly referred to as a chopper, is used to compare the electronic counter voltage with the output from the linear potentiometer. The arm of the chopper alternately connects to each potential source at a 60-cycle rate and produces a 60-cycle output when any potential difference exists. The magnitude of the 60-cycle output is directly proportional to the difference in the magnitudes of the two potential sources. The relative phase of the 60-cycle output depends upon which potential has the greater magnitude. If there is any signal output from the chopper, the servo motor operates, in a direction governed by the relative phase of the chopper output until the potentiometer arm is moved to a position that reduces the chopper output to zero.

The manner in which the preceding operating is executed is quite conventional for small servomechanisms of the potentiometer variety. The first amplifier tube V601A is connected as a cathode follower in order to greatly reduce loading the output of the electronic counter unit. The gain of the cathode follower is controlled by means of switch S602-A to insure that the servo sensitivity is the same for



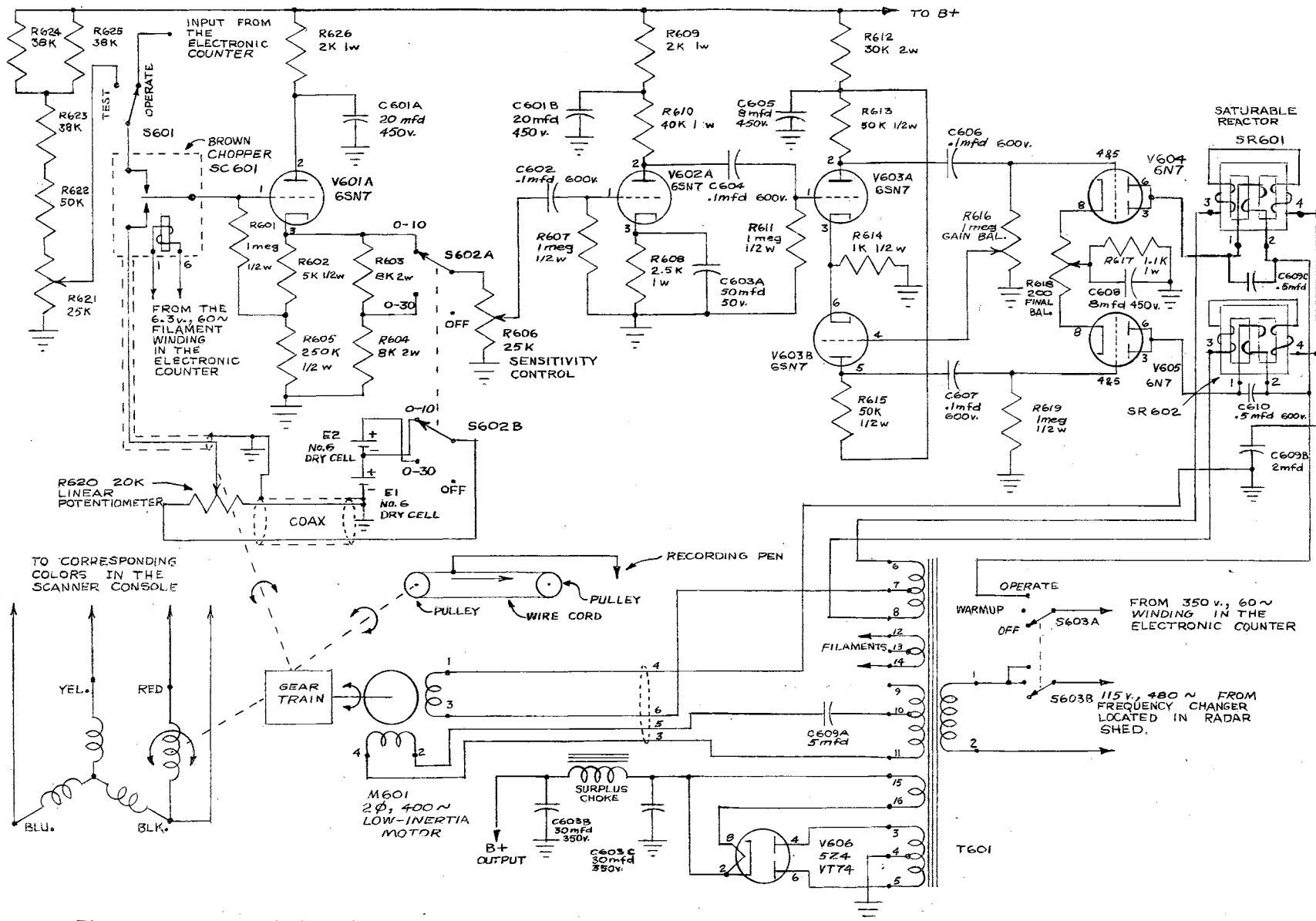


Figure 33. Pen-Drive Servomechanism Circuit Diagram.

the two scales provided. The other switch section S602-B functions to select the full scale sensitivity of the recorder by changing the reference voltage applied to the linear potentiometer. Two No. 6 dry cells furnish the potential source for the potentiometer. On the 0-10 scale only one of the cells is used. For the 0-30 scale, the two cells are connected in series across the linear potentiometer.

The output from the cathode follower appears across resistor R606, and a portion of this output is selected to be fed on to the following amplifier stage. Resistor R606 is the sensitivity control and is adjusted to provide a maximum rate of servo motor response with negligible overshoot. The sensitivity can be set so high that the servo loop gain is enough to cause the system to continuously oscillate. The proper sensitivity setting can easily be obtained by placing switch S601 in the test position and adjusting the sensitivity control so that the rate of response to the test signal is maximum when zero overshoot is experienced.

The output from the sensitivity control is fed to tube V602A, which is connected as a conventional amplifier stage. The output from tube V602A is fed to the first section of tube V603, which is connected as a phase splitter<sup>2</sup>. An oscilloscope can be used to adjust the output of tube V603B to the same value as that obtained from V603A. This is best performed when tubes V604 and V605 are removed from their sockets.

Tubes V604 and V605 are connected in a phase detector circuit, with the reference phase voltage applied to both plate circuits simultaneously. The 60-cycle reference phase voltage is obtained from the

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<sup>2</sup>Ibid, p. 114.

power transformer T501 in the electronic counter. The 6.3-volt sixty-cycle potential used to drive the vibrating contacts of the chopper is also obtained from this source.

The phase detector directly controls the action of the servo motor M601. The two-phase motor has one phase, winding 2-4, permanently excited by the 480-cycle source. The second phase is connected in a bridge-circuit arrangement to the phase detector. A center-tapped winding on the 480-cycle transformer T601 (Terminals 6-7-8), is connected to supply the second phase, winding 1-3, through the a-c windings of saturable reactors SR601 and SR602. The d-c windings of the two saturable reactors are in the respective plate leads of the phase detector tubes. Under balanced conditions, the plate currents of the two phase detectors are equal. When unbalanced conditions exist, one detector tube conducts heavier than the other because of the relative phase of the sixty-cycle error signal from the chopper. The phase detector tube, which conducts the most, is the one whose grid error signal is in phase with the reference phase voltage applied to both phase detector anode circuits. The extra conduction current through this phase detector tube causes the corresponding saturable reactor to allow the proper phased 480-cycle potential to be applied to the 1-3 winding of the two-phase motor. The servo motor then turns the potentiometer arm to such a position that the chopper output error signal is zero. Thus, the pen is driven to a position corresponding to the d-c voltage received from the electronic counter.

A selsyn transmitter<sup>3</sup> is connected to the potentiometer arm and

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<sup>3</sup>J. Francis Reintjes and Godfrey T. Coate, Principles of Radar (New York, 1952), pp. 277-292.

transmits the indication of the counter to a remote indicator, located on the front panel of the scanner console. The scanner console unit will be discussed in the following section.

#### Scanner Slit-Driver Servo

One of the chief advantages of the HFDF counter is that the scanner can be synchronously driven by remote control. The desired action is accomplished by means of a servomechanism that is controlled by a small synchronous motor. Once the unit has been synchronized with the laboratory master time clock, the time of each subsequent record is accurately known and does not have to be continuously recorded during the progress of a storm but can be filled in at a later date when operator time is not at such a premium.

The schematic diagram of the scanner slit-drive servomechanism is shown in Figure 34. The major portion of the circuit components are war surplus parts from an aircraft-type radio direction finder. In the lower right-hand portion of the drawing is shown the 1/6 rpm synchronous drive motor, which is coupled by a friction clutch to the rotor of a selsyn transformer<sup>4</sup>. The companion selsyn SEL 702 is mechanically coupled to the scanning slit drive shaft. The rotor of selsyn SEL 702 is fed directly from a winding of the 480-cycle transformer. If the rotor winding of SEL 703 is mechanically perpendicular to the magnetic field transmitted from selsyn SEL 702, zero voltage is induced into the rotor winding. However, should some slight angular deviation from this perpendicular relation exist, a voltage will be induced into the rotor

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<sup>4</sup>Radar System Fundamentals (Washington, 1944), p. 323.

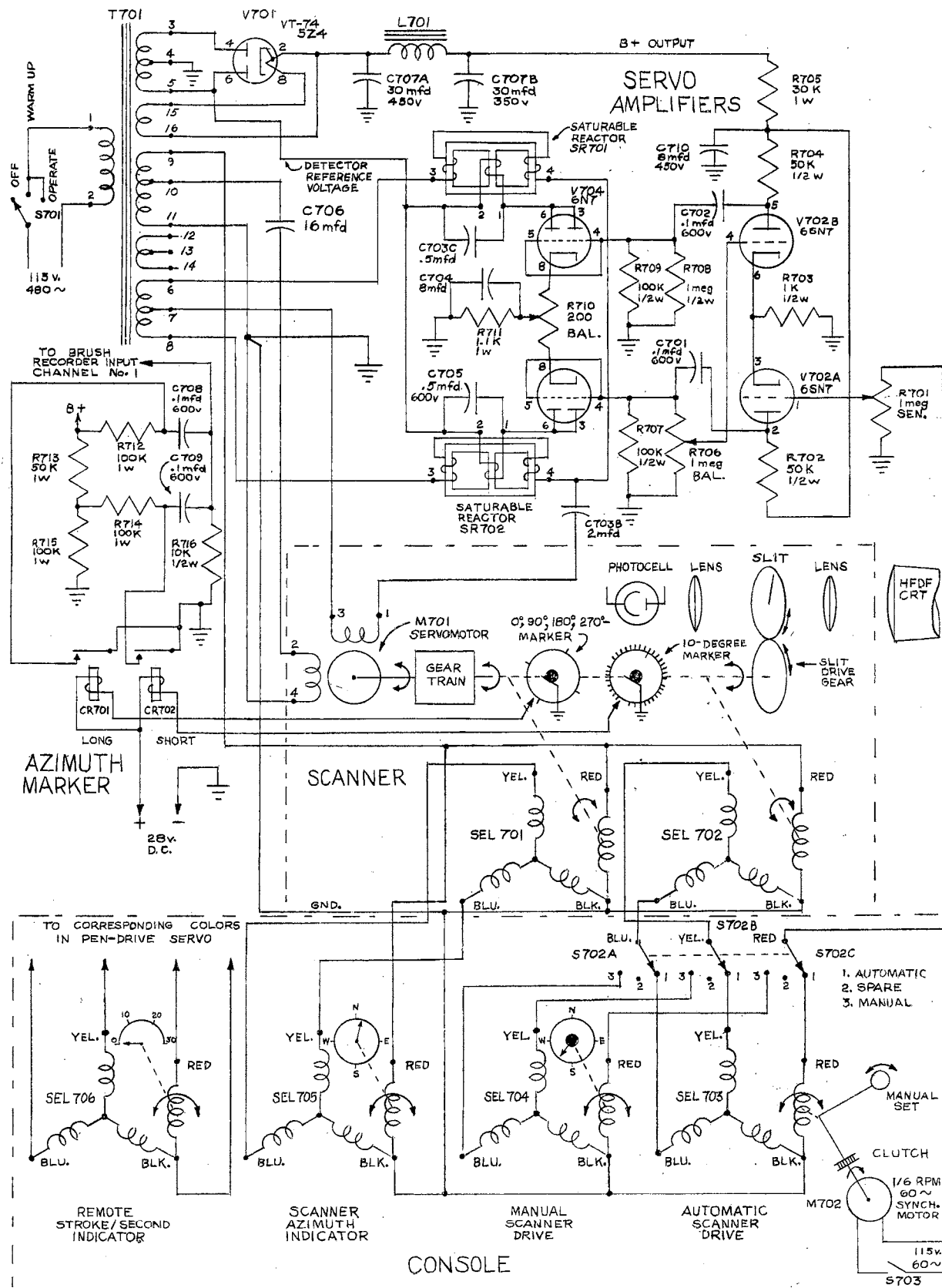


Figure 34. Circuit diagram for the Scanner Slit Drive Servomechanism.

winding whose magnitude is proportional to the sine of the deviation angle and whose relative phase depends upon the relative deviation of the rotor from the perpendicular position.

The purpose of the servo amplifier unit is to detect the angular deviation and to operate the scanner servo motor in such a direction as to reduce the induced rotor voltage of SEL 707 to zero. The gear train of the scanner servo motor is chosen so that the scanning slit closely follows the demands of the synchronous drive motor. Under these conditions, the scanning slit follows the demands of the synchronous motor as far as velocity requirements are concerned, with just enough position error to keep the angular velocity constant at the one-degree per second rate.

The electrical action of the servo amplifier circuit is basically the same as that of the corresponding section in the pen-drive servo unit, except that all signal voltages in this unit are 480-cycles instead of 60 cycles. The angle-error signal from the selsyn transformer is of sufficient magnitude that the output can be fed directly into the phase splitter circuit, tubes V702A and V702B, without additional amplification. The sensitivity control R701 is located in the grid circuit of tube V702A and should be adjusted to give the proper characteristics to the scanner motor. Under no condition should the sensitivity control be adjusted to give so much loop gain that the system has any oscillating tendency.

Tubes V702A and V702B are connected as a phase splitter to develop equal-amplitude error signals that are oppositely-phased at the grids of tubes V703 and V704. Tubes V703 and V704 act as phase detectors to determine in which direction the scanner servo motor must rotate in

order to reduce the error signal to zero. The 480-cycle anode reference voltage, applied to the phase detector circuit, is obtained from one-half of the high voltage winding of the power transformer, pin 5 of transformer T701.

When an error signal exists, one of the phase detector tubes conducts more than the other and saturates the corresponding saturable reactor in its plate circuit. This action results in the proper phased voltage being applied to the scanner servo motor winding and the servo motor rotating in the correct direction to reduce the error signal to zero. In this particular application, however, the 1/6 rpm synchronous motor continually moves the rotor of selsyn SEL 703 at a rate of one degree per second; and, as a result, a certain error signal is always produced which keeps the scan motor rotating at identically the same angular velocity as the synchronous motor. Thus, the scanning slit is caused to scan the complete 360 degrees of azimuth every six minutes. If the scanner slit is at zero degrees before the synchronous motor is started, it can be started so as to synchronize the scanning action with the master time clock. The friction clutch is used to position the scanner slit at the zero-degree position.

The master time clock is initially synchronized with the time signals from the Bureau of Standards radio station WWV. The automatic scanner drive motor is started on the hour or at the beginning of any six-minute period after the hour. Because of this condition, the zero-degree position of the scanning slit is known to occur exactly on the hour and every six minutes after the hour, and no continuous time log need be kept. The day following the storm, the time can be written in to correspond to each zero-degree point on the paper tape record.

In order to facilitate the interpretation of the paper tape record, azimuth marks are placed at 10-degree intervals along the recording. A two-pen Brush recorder was obtained for the purpose of recording the output of the electronic counter. The two Brush pen-motor units are employed to code the paper tape record, while the pen-drive servo is used to actually record the stroke rate. One of the Brush pen-motor units is used to place the azimuth marks along the paper tape record at 10-degree intervals; the other Brush pen-motor unit is used to indicate the time during which the waveform analyzer recording camera is operating.

The azimuth-marking pen requires a voltage impulse to its controlling amplifier. These impulses are generated by a circuit shown at the left side of Figure 34. Two relays CR701 and CR702 function to produce the desired impulse signals across resistor R716. When relay CR701 is energized, condenser C708, which is charged to the full potential of the power supply, is suddenly connected across resistor R716, producing an exponential impulse. The operation of relay CR702 results in an identical action with condenser C709. Condenser C709, however, is charged only to two-thirds of the power supply potential and thus produces a smaller amplitude exponential pulse of voltage across resistor R716. It should be noted that since the negative terminal of each condenser is connected to the top of resistor R716, it produces a negative-polarity signal at that point. The signal is connected to the azimuth-marking Brush amplifier.

Relays CR701 and CR702 are energized at regular intervals by radial wire contacts on two spur-like switches, which are driven by the scanner servo motor. One of these spur-like switches has radial wires at each 10-degree interval exclusive of the cardinal points  $90^{\circ}$ - $180^{\circ}$ - $270^{\circ}$  which



make electrical connection to a spring-like contact that controls the operation of relay CR702. The other spur-like switch has only four radial wires adjusted to energize relay CR701 at the four cardinal points. The wire on the 10-degree spur-like switch, originally intended to represent the zero degree point on the azimuth scale, has been bent so that it causes one marker to appear at an azimuth of  $4^{\circ}$ . This marker at the  $4^{\circ}$ -point distinguishes the zero-degree point from the other three cardinal points, which are followed by 10-degree markers. Thus, the azimuth markings on the paper tape record consist of short marks at each  $10^{\circ}$  azimuth point other than the cardinal points, and long marks at each of the cardinal azimuth points with the long zero-degree mark followed by a short mark four degrees later.

#### Placing the HFDF Counter in Operation

The operation principles for the HFDF counter are relatively straight forward, but the procedures necessary to insure proper operation are unique. The accuracy of the records depends upon the accuracy with which the scanning slit rotates about the axis of the optical system, upon the accuracy of the HFDF presentation alignment relative to the axis of the optical system, and upon the accuracy of the azimuth marks relative to actual scanning slit location. If proper procedures are employed in the initial tuning of the HFDF receiver units and a cathode-ray tube with exact perpendicular deflection characteristics is employed to display the spheric activity, the electrical output signals from these units bear the proper ratios for correctly identifying the spheric azimuth.

The manufacturer of the cathode-ray tubes does not maintain exact

perpendicular deflection characteristics in all tubes. Yet, a tube can be found which has almost exactly a perpendicular deflection characteristic. The cathode-ray tube presently employed in the HFDF counter is such a tube, and in addition, displays an extremely small-diameter, well-focused electron-beam. If the deflection system is not exactly perpendicular, two quadrants exhibit 90-electrical-degrees in a physical sector which is somewhat less than  $90^\circ$ ; while the other two quadrants exhibit 90-electrical-degrees in a physical sector which is somewhat greater than  $90^\circ$ . This distorted azimuth display can be tolerated on the paper tape record as long as the spur-type azimuth marker switches are adjusted to indicate the corresponding angular points. It is desirable to have a cathode-ray tube with exactly perpendicular deflection characteristics because the visual azimuth indicator, a selsyn indicator controlled by the slit drive shaft, has a normal azimuth distribution, and any distortion of the azimuth presentation on the cathode-ray tube would be extremely difficult to correct.

Three problems arise in the alignment of the cathode-ray tube display and the axis of rotation of the scanning slit. The focusing of the HFDF presentation at the plane of the rotating slit and the aligning of the scanning slit so that it passes through the center of rotation of the gear upon which the slit is mounted pose severe problems. Perhaps the most difficult task is encountered when the cardinal points of the HFDF scope presentation are adjusted to correspond to the cardinal point positions of the scanning slit. A consideration of the logical order in which these operations should be performed suggests that the focusing operation should be first. It was found, however, that a much better focusing adjustment could be made after the scanning

slit position is adjusted to correspond to the axis of the drive gear upon which it is mounted.

A bright light is placed on the photocell side of the scanning slit and a piece of white paper placed on the scope side of the lens in such a position that the image of the scanning slit is in sharp focus on the paper. The position of the slit image is then marked on the paper, and the drive gear upon which the slit is mounted is rotated  $180^{\circ}$ . If the radial slit is in proper adjustment, the two images of the slit are colinear; if not, they are parallel and displaced from one another a distance twice the amount of misadjustment. Should the slit need adjusting, it is then moved slightly in the direction indicated by the position of the two images. The process is repeated until the desired colinear position of the two images is obtained. Once this adjustment has been made, the slit does not need re-adjusting unless it is removed from the drive gear. In this case, the whole procedure must be repeated.

The scanner door is swung into position in order that the focusing operation can be performed. A straight-line HFDF presentation is obtained by placing the HFDF receivers in the tune position. The image of this HFDF presentation is then focused on the plane of the scanning slit. This focusing adjustment can be performed easily by placing a thin sheet of paper against the scanning slit on the lens-side and sharply focusing the image on the paper. The paper is then placed against the slit on the phototube-side and the image re-focused. While performing this second operation, one observes the image on the lens-side of the scanning slit. After the two settings of the lens position have been noticed, a proper setting can be determined which gives

satisfactory results. The lens must be clamped in position, for any slight movement results in a great displacement of the image position relative to the axis of the scanning slit.

The most difficult adjustment results from the trial and error method employed in aligning the cardinal points of the HFDF scope presentation with the cardinal point positions of the scanning slit. An easier method, devised subsequent to the initial installation, should be used in case the cathode-ray tube needs to be replaced. Now that the exact position of the HFDF presentation has been determined by the trial and error method, it is easy to construct a sturdy plexiglas jig, which fits into the bezel of the oscilloscope and has cross hairs that coincide with the center of the cathode-ray tube display and the four cardinal points of the presentation. With such a jig keyed in position, a new cathode-ray tube can be inserted and rotated until its deflection directions correspond to the hair lines on the jig.

The initial determination of the correct cathode-ray position was made by trial and error. The HFDF receiver units are placed in the tune position to obtain a straight line cathode-ray tube display. The image of the display is visually observed from the phototube-side of the scanning slit as the slit is rotated past the angle represented by the HFDF presentation. When the center of the display is in the proper position and the angular position of the display corresponds to the proper angular position of the scanning slit, a slow rotation of the scanning slit results in the entire length of the scanning slit being illuminated simultaneously. If either the center of the display or the angular position of the display does not exactly agree with that of the scanning slit, a slow rotation of the scanning slit results in

only a portion of its slit length being illuminated at any one position. This illuminated portion appears to move along the length of the slit as it is rotated. From the nature of the observed indication, the cathode-ray tube is rotated, and the positioning voltage re-adjusted until the desired result is obtained. The adjustment is simplified somewhat by using only a north-south cathode-ray-tube display and employing only one positioning control.

Once the north-south axis of the cathode-ray-tube display has been adjusted to coincide with the north-south position of the scanning slit, it is relatively simple to locate the origin which must be used for the display. The scanning slit is merely rotated to the east-west position; the HFDF receiver unit is adjusted to produce the east-west tuning display; and the other positioning control is manipulated until the image of the display coincides with the scanning slit. If neither positioning controls are moved from their settings as determined by the preceding adjustments, the rest position of the cathode-ray-tube beam corresponds to the origin required for proper operation in conjunction with the lens and the scanning slit. This position is marked in India ink directly on the face of the cathode-ray tube to facilitate rapid alignment during the tuning procedure.

Once the optical system is in proper agreement with the scanning slit, cathode-ray-tube presentations can be displayed at various azimuth positions to check the accuracy of the corresponding angles indicated by the scanner azimuth indicator. It has been found that the angular agreement between the HFDF presentation and the scanner azimuth is within one-degree. If the scanner azimuth indicator is used as a reference, the various wires of the spur-type azimuth marker switch are bent

accordingly until the azimuth marks on the paper tape record agree with the indication of scanning slit position.

At the beginning of a storm, the various controls must be properly set to insure that the automatic recording of active spheric angles is reliable. The first requirement is that the HFDF receiver is properly tuned and balanced. Next, the vertical and horizontal positioning controls of the counter oscilloscope must be adjusted to make the counter HFDF presentation coincide with the India ink reference marks on the face of the cathode-ray tube. It is best to adjust the HFDF receiver switches to the tuning positions which cause only a north-south cathode-ray-tube display. One then manipulates the east-west positioning controls, vertical, until the display exactly coincides with the north-south reference lines on the face of the cathode-ray tube. The same procedure is then repeated for the east-west display.

When the two positioning adjustments have been made, the origin and the four cardinal points are in proper alignment. Unless the deflection amplifiers are properly balanced, all other azimuth directions are in error. With the tuning controls on the HFDF receiver set to produce signals representing the  $225^{\circ}$  azimuth display, the gains of the vertical and horizontal deflection amplifiers of the counter scope are manipulated until the oscilloscope display coincides with the India ink reference line representing the  $225^{\circ}$  azimuth point. The oscilloscope adjustments are complete at this point. The counter should be calibrated to produce voltages which correspond to its scale markings.

The tuning pulse generator can be set to generate pulses at  $1/2$  the power line frequency. Under these tuning conditions, the

oscilloscope display can be set at the  $225^{\circ}$  position and represent an active spheric angle whose repetition rate is approximately 30 per second. The counter is operated on the 0-30 scale and switch S-702 (Figure 34) is set to position 3. The manual scanner drive, selsyn SEL704, is set to the  $225^{\circ}$  position and is allowed to assume this azimuth position. The counter pen drive should immediately start to indicate a stroke rate of approximately 30 per second. The regulated power supply, which feeds power to the electronic counter chassis, is adjusted until the counter pen indicates the proper position corresponding to the mark on the scale for this adjustment. This step completes the calibration of the counter unit.

The station clock must be synchronized with the time signals of radio station WWV before the automatic scan drive motor can be started. A communications receiver is tuned to one of the transmission frequencies of station WWV. The 10-megacycle and 15-megacycle transmissions are most easily received in this section of the country. Although the modulation content has been changed in the last few years, the transmission is consistent during the last minute, out of every five-minute interval. On the hour and on every five-minute period after the hour, a tone signal commences. Alternate five-minute periods provide a 600-cycle tone; the remaining five-minute periods provide a 440-cycle tone.

The laboratory clocks can all be stopped by a master clock switch, and each clock can have individual power applied by means of a jog switch. When the master clock switch is in the off position, all clocks are operated by means of the respective jog switches until the second hands are exactly on 12. The WWV transmission is monitored for

the voice transmission which precedes each five minute interval by approximately 20 seconds. The announcer gives the station identification and Eastern Standard time as follows: "Radio Station WWV. When the tone returns, Eastern Standard Time will be -----." There is a slight pause and the time is repeated. The tone can be anticipated because the 1-cps time click representing the 59th second is omitted; and then, the tone begins. The laboratory master clock switch should be thrown at exactly the start of the tone.

The manual-set knob of the automatic scanner drive should be rotated counter-clockwise until the scanning slit is exactly at the zero-degree point. Rotation in the counter-clockwise direction is necessary in order to take out the backlash in the synchronous drive motor gear box. The synchronous drive motor can be started, on the hour or at the start of any six-minute period after the hour, by means of switch S703; for example, 18 minutes after the hour or 30 minutes after the hour, etc. Because of the initial lags in the scanning system, the synchronous drive motor switch should be started 1-second prior to the six minute period to insure exact synchronization. The starting time should be logged on the paper tape record adjacent to the zero azimuth mark which represents this starting time. The scale of the counter, 0-30 or 0-10, should also be logged on the paper tape record, and any time that the scale is changed a note should be placed on the paper tape record. Since the gain of the HFDF receiver unit affects the counter indication, any receiver gain or any gain change should be noted on the paper tape record. All of the operating conditions must be taken into consideration in the subsequent analysis of the paper tape record. For this reason, it is imperative that these conditions be accurately logged.



Except for these minor logging activities, the functioning of the HFDF counter unit is completely automatic.

### Interpretation of Counter Records

The description of the physical construction of the scanning slit and its accompanying aluminum mask indicate that a stroke must be of sufficient strength to cause a presentation to be counted. The closer the aluminum mask is to the axis of slit rotation, the smaller are the magnitude requirements for a stroke that can be counted. The production of sferics from a given storm center is at a more or less erratic rate, rather than periodic. The storm center must, therefore, produce a representative amount of activity at the particular interval during which it is being scanned in order for it to be accurately gauged by the counter. The only way that the record can be representative of the intensity of the storm is for the scanning slit to observe a particular storm center long enough. These requirements practically demand that the scanning slit observe all azimuth angles continuously, rather than at regular intervals. Indeed, this is the desirable thing to do; even though it is rather impractical with the present system of recording. Two systems have been proposed which could monitor a storm center in a continuous manner, but neither has been tested experimentally.

When test pulses are presented on the HFDF scope at  $225^{\circ}$  and the counter allowed to scan this presentation, a count can be produced over the angular interval of  $224^{\circ}$  to  $226^{\circ}$  depending upon the radial setting of the aluminum mask. For the example just cited, the scanning slit is said to have an effective width of two degrees, which

might exist when the active portion of the slit is approximately  $5/16$  of an inch from the axis of rotation. Under these conditions, the slit scans an annular sector in which the inner radius is  $5/16$  of an inch. As the aluminum mask is moved closer to the axis of rotation, the effective slit-width increases and can be as great as 10 to 15 degrees when the mask is very near the axis.

During the 1956 tornado season, the aluminum mask was set  $3/16$ -inch from the axis of slit rotation, a situation which resulted in an effective slit width of approximately 5 to 8 degrees. The effective slit width varies slightly with azimuth because of the difficulty of perfectly aligning the imaged HFDF-presentation with the axis of slit rotation. This action results in some error in azimuth indication, but the original tests revealed this error to be less than one-degree for the four cardinal points and the NW, NE, SW, and SE points. The alignment procedure is engineered to give reproducible results if the operator exercises reasonable caution in the various alignment steps.

The film record, which records time exposures of the HFDF presentation, indicates that even on very active storms, a certain spheric center can be exceedingly prominent on the one-second time exposure and non-existent on the two-second and the five-second time exposures. This condition indicates that because of the erratic behavior of a storm center in regard to spheric activity, a particular one can appear to be very active overall. Nevertheless, it can be dormant for short periods of time at certain intervals. For this reason, the counter record should be interpreted over several consecutive scans to determine the severity of the storm.

The scanning device of the counter, which moves at a rate of one-degree per second and exhibits a 5 to 7-degree effective scanning slit width, observes a particular azimuth only about 5 to 7 seconds during a six-minute period. The azimuth position of the pen on the paper tape record corresponds to the center position of the scanning slit. If the activity from a given storm center is especially severe on one six-minute scan when the slit is as far advanced as possible and is just as far retarded as possible during the next scan interval, the paper tape record can show the recording to be as much as seven degrees different on the two successive scans. The true position of this active angle is  $3.5^{\circ}$  different from that of each recording. Although this is an idealized example, the true position may not be the azimuth midway between the two recordings. In this case, one would be uncertain as to the exact location of the true active angle from just observing the paper tape record.

The preceding analysis holds true if the storm activity is presented as an extremely fine line on the HFDF scope face. The activity is very intense over a sector several degrees wide. It might well be that the paper tape record shows the recordings on consecutive scans to be different by as much as ten degrees. Almost all actual recordings are much closer to the true azimuth than this theoretical discussion implies. The visual HFDF indicator should be employed to judge the center of the activity very closely, and the counter record used to determine the intensity index of the various storm centers.

## CHAPTER VI

### THE CAMERA CONTROL UNITS

When the project began, the recording of film data was left entirely to the discretion of the operator. As more and more equipment was developed, however, it became impossible to secure an integrated set of data. The first step toward the automatic recording of data was the construction of a simple electrical timer, which controlled the camera used to photograph the display of the dual scope unit. A more elaborate relay-operated device was constructed to automatically operate the radar camera. After the dual scope unit had been modified to function in two modes of operation, it became apparent that a master camera control device would be desirable. Such a device was not constructed immediately, because more important developments were necessary.

In the spring of 1954 it was noted that whenever time exposures of the HFDF display were accidentally recorded, they greatly aided in the analysis of the film record. Dr. Helmut Weichmann of the Evans' Signal Laboratories suggested that a Polaroid camera be employed to record these time exposures for use during the progress of a storm. Because such a camera was not readily obtainable, a scheme was conceived whereby the regular 35 mm camera could be controlled to take time exposures of the direction finder displays for several pre-determined lengths of time. Mr. Wayne Staats, a United States Weather Bureau Meteorologist, and Mr. Marvin Turrentine, a graduate student, suggested the various lengths of time exposures which would be desirable from the standpoint

of the film analyst. The composite picture unit was designed and constructed to satisfy these requirements. The name composite picture unit describes the nature of the type pictures resulting from a time exposure of the direction finder, a composite picture of the various active storm centers. Probably the name more amply describes the overall master control the device exercises over the recording cameras. It not only controls the taking of the required group of time exposures but also controls the recording of the regular waveform camera run every five minutes when the waveform analyzer operates in both modes of operation and the radar camera at either one record per minute or one record every five minutes. The electrical operation of the composite picture unit is described in a subsequent topic of this chapter.

#### Waveform Analyzer Camera Control Unit

In order to simplify the overall explanation of camera control, it is desirable to discuss the operation of each individual camera control and then to discuss how these fit in with the composite picture unit. The device which controls the waveform analyzer camera is a modified timer designed for use in training Air Force gunnery students.

The schematic for the waveform analyzer camera control unit is shown in Figure 35. Although the electrical action is quite simple, a few control circuits are employed which warrant some explanation. The circuit composed of relays CR3 and CR4 is a relay-type counter<sup>1</sup> which is employed frequently in the various camera control circuits.

The control impulse from the composite picture unit, which initiates

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<sup>1</sup>W. Kiester, A. E. Richie, and S. H. Washburn, The Design of Switching Circuits (New York, 1951), p. 242.

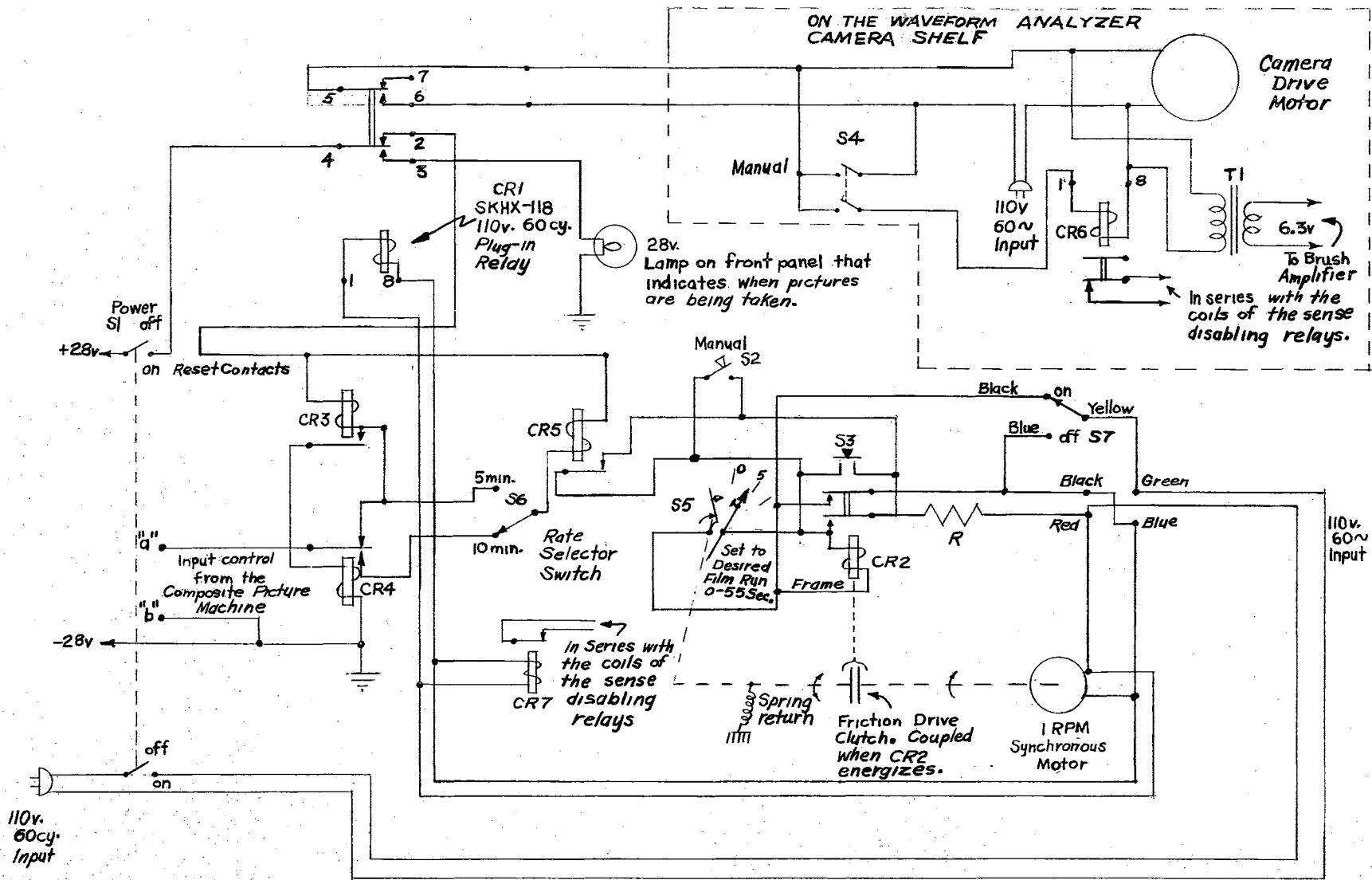


Figure 35. Circuit diagram of the Waveform Analyzer Camera Control Unit.

the circuit action, consists merely of a complete electrical connection being applied between the two points "a" and "b." With the power switch on, 28 volts are applied to the counter circuit via the normally-closed reset contacts of relay CR1. The initial connection between points "a" and "b" causes relay CR3 to energize and connect itself and relay CR4 in a series. However, the electrical connection existing between points "a" and "b" by-passes the current around relay CR4 and prevent its energizing. The input control from the composite picture unit consists of momentary connection of the points "a" and "b." Immediately upon the termination of this connection, relay CR4 is allowed to energize as a result of the series current through CR3 and CR4. The contacts of relay CR4 transfer the connection of terminal "a" into the rate selector switch. The rate at which input control impulses arrive from the composite picture unit is one every five minutes. If the rate selector switch is in the position indicated in the drawing, two input control impulses are required before relay CR5 will energize. The contacts of relay CR5 start the timing process. If the rate selector switch is in the 5-minute position, the initial impulse from the composite picture unit would have been applied directly to relay CR5 and the timing process would have begun immediately. The sole purpose of relays CR3 and CR4 is the storage of the first impulse information if the camera is to be operated only every 10 minutes instead of at the impulse rate of once every five minutes.

If additional camera runs are desired, either of the manual switches, S2 or S3, can be depressed in order to start the timing operation. It begins when relay CR2 is caused to energize by either the manual push buttons or the automatic action of relay CR5. Relay CR2 is provided with

holding contacts which insure proper operation even though the manual control switches are depressed momentarily. Relay CR2 also applies power to the 1-rpm synchronous motor and causes the friction-clutch drive of switch S5 to engage. When power is applied to the synchronous drive motor, it also causes relay CR1, parallel with the motor, to energize. The contacts of relay CR1 apply power to the camera drive motor and remove the 28-volt d.c. source from relays CR3, CR4, and CR5, allowing them to reset.

When the synchronous timing motor drives the spring-return arm of switch S5 into contact with the adjustable arm, the coil of relay CR2 is electrically shorted. The action causes this relay to de-energize immediately. Resistor R limits the current drawn from the 110-volt source during the interval that relay CR2 is short-circuited. The de-energizing of relay CR2 results in the stopping of the synchronous timing motor, the de-coupling of the friction-drive clutch, and the de-energizing of control relay CR1. As a consequence of these actions, the camera-drive motor is stopped and the spring return arm of switch S5 moves back to the zero position. The length of time that the camera is operated depends upon the initial setting of the adjustable arm of switch S5. Any desired length of camera run can be set within the range of zero to fifty-five seconds.

In the section of the drawing which depicts the camera drive motor a number of additional features bear consideration. A manual switch S4 is provided so that the camera can be operated for periods which are greater than 55 seconds in duration. An auxiliary relay CR6 is employed to furnish additional contacts for the purpose of overriding the control of the composite picture unit regarding the direction



finder sense receivers when it is desired that manual control be exercised over the recording of waveform analyzer film records. Transformer T1 is utilized to obtain a 6.3-volt, 60-cycle signal to feed to one of the Brush amplifier units whenever the camera drive motor is in operation. This signal places on the paper tape of the HFDF counter a record of the exact time when film records are being made. Should any trouble develop in the camera equipment, the operator could quickly detect its presence by observing the paper tape record. This feature is important to the film analyst for determining exactly when corresponding counter and film records are available.

#### The Radar Camera Control Unit

It is the purpose of the radar camera control unit to record automatically three consecutive pictures of the radar cathode-ray tube display for each control impulse that is fed to the input of the unit. The camera, which is controlled by the unit, employs rotary relays to advance the film after an exposure has been made. Each time an impulse arrives at the input of the camera control unit, the radar scope is activated and the first frame of film is exposed for two complete revolutions of the radar antenna. After the first antenna revolution has been made, a set of lights is flashed to illuminate the clock, the date card, and the azimuth markings so that this data appears on the film record. At the end of the exposure, the camera relays are energized and the film is advanced. During the next two antenna rotations, a second frame of film is exposed and advanced. This process is repeated once more during the next two antenna rotations. Then the camera control unit automatically shuts off, awaiting the next control impulse.

The entire cycle requires six rotations of the antenna and provides three consecutive pictures of the radar scope presentation.

The schematic of the radar camera control unit is shown in Figure 36. The input power is obtained from the same 28-volt d.c. source used to supply the radar set. Relay CR12 is energized when it is desirable to begin a cycle which results in the three film records. It has been indicated in the drawing that push button S1 can be depressed to start the camera cycle. This switch is normally employed only to test the operation of the unit while one is in the radar van. A similar switch inside the laboratory is used to repeat the camera cycle at regular intervals of one minute or five minutes. Switch S2, which is in parallel with the push button S1, can be operated to make continuous camera records.

The contacts of CR12 act as holding contacts to keep this relay energized throughout the cycle. These contacts also function to provide a complete electrical path to a number of other relays in the unit. Whenever this holding contact circuit is interrupted, the unit resets. The holding circuit is completed through the normally open contacts of relay CR18. At the end of the cycle, relay CR18 energizes momentarily and resets the entire unit.

After relay CR12 is energized by the initiating action of switch S1, the #49 contact of the antenna microswitch has an electrical connection to ground through the contacts of CR7 and CR12. As the antenna rotates, the antenna microswitch closes and causes relay CR11 to energize. The contacts of relay CR11 provide a complete electrical path for relays CR8, CR9, and CR10. A single multiple contact relay could perform the function of all three of these relays. However, only

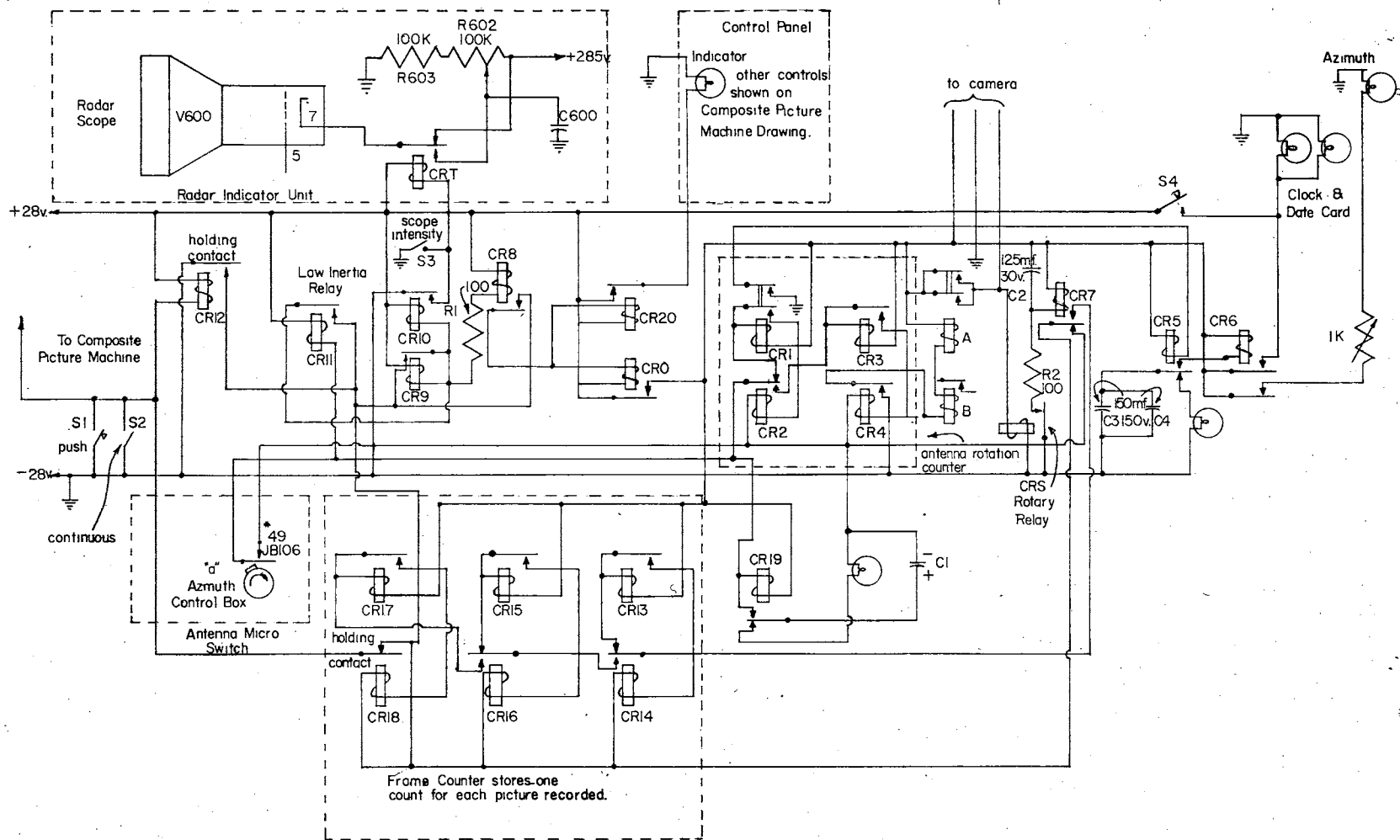


Figure 36. Circuit diagram of the Radar Camera Control Unit.

a multitude of single-pole surplus relays were readily available at this time. The contacts of relay CR9 act as holding contacts for the three relays. The contacts of relay CR10 function to control relay CRT, which is located inside the radar indicator unit. The radar pattern appears on the face of the radar scope whenever relay CRT is energized. Whenever it is desirable to observe the scope presentation for checking purposes, auxiliary switch S3 makes it possible for the radar scope to be operated manually. The contacts of relay CR8 act to energize relays CR20 and CRO.

The indicator lamp, which is controlled by relay CR20, provides the operator inside the laboratory with a visual indication that a set of radar pictures is being made. Relay CRO functions to apply the 28-volt power to the other relays of the radar camera control unit. At this point of the cycle, when the 28-volt source is available to all the relay circuits, it is possible for the antenna rotation counter and the frame counter to function whenever control impulses are applied to their respective input circuits.

The first closure of the antenna microswitch after the cycle is initiated, results in the activation of the radar scope and the application of power to the entire control circuit. The second closure of the antenna microswitch is coupled into relay CR2 of the antenna rotation counter circuit. Because of the extremely short time interval during which the antenna microswitch is closed, an auxiliary relay CR19 is connected to provide a closed electrical path for a long enough period of time that the counter relays function.

The antenna rotation counter consists of relays CR1, CR2, CR3, and CR4. After the cycle begins, the second time the antenna microswitch

closes, a connection to ground exists at the arm of relay CR2. This action causes relay CR1 to energize and connect its coil in series with the coil of relay CR2. The coil of relay CR2, however, is still short-circuited by the action of the antenna microswitch and relay CR19 and cannot energize. After the antenna microswitch opens and relay CR19 de-energizes, the short circuit no longer exists and relay CR2 energizes. Although relay CR1 and CR2 are rated as 28-volt relays, their springs have been weakened in order that they can stay energized on half voltage. A second set of contacts on relay CR1 cause relay CR5 to energize and the results of this action will be considered before discussing the result of relay CR2 energizing.

The contacts of relay CR5 are connected to place an uncharged condenser in series with relay CR6, causing the momentary operation of relay CR6. As the contacts of relay CR6 rapidly close and open, the clock, date, and azimuth lights are flashed to provide this data on the film record.

It is noted concerning the action of counter relay CR2 that its contacts transfer the connections from the antenna microswitch into the coil of relay CR3. Relay CR3, therefore, energizes on the third closure of the antenna microswitch. Relay CR4 energizes upon the termination of the third closure of the antenna microswitch. The contacts of relay CR4 cause CRA and CRB to energize. The heavy contacts of relay CRA apply the 28-volt power to the radar camera, an action which requires approximately ten amperes at this voltage. As power is applied to the camera, the camera relays operate to advance the 35 mm film to another frame in preparation for a second film record. The contacts of relay CRA also cause rotary relay CRS to energize. The high inertia of the rotary relay CRS

provides some delay before its contacts are actuated.

Relays CRS and CR7 function to terminate the application of power to the camera. Sufficient delay time must be provided in order that the camera relays have time to act. Relay CR7 provides additional delay time as a result of the action of resistor R2 and condenser C2. Condenser C2 is uncharged when power is applied to the circuit, and it must charge through resistor R2 to a sufficient degree before relay CR7 energizes. As the contacts of relay CR7 operate, the ground is removed from the antenna rotation counter relays, resetting them in preparation for the next film exposure, and storing a count in the frame counter. The frame counter, which consists of relay CR13 through CR18, stores one count for each picture recorded. For the first count, relays CR13 and CR14 are energized. The contacts of relay CR14 are connected to transfer the input from relay CR7 on to relays CR15 and CR16 in preparation for the next film count.

The second and third closure of the antenna microswitch result in the recording of one radar film record; the fourth and fifth closures result in the recording of the second film record. At the fourth closure of the antenna microswitch, relay CR7 energizes again and stores a second count in the frame counter circuit on relays CR15 and CR16. It also resets relays CR1 and CR4 in preparation for the third film record.

The sixth and seventh closures of the antenna microswitch result in the recording of the third film record. At the end of the third film recording, relay CR7 stores another count in the frame counter on relays CR17 and CR18. As relay CR18 energizes, the ground is removed from the coil of relay CR12, resulting in removal of the 28-volt power from the entire circuit. This action completes the cycle and the unit is completely

reset awaiting the beginning of the next cycle.

Additional features which should be noted include switch S4, which can be depressed to obtain light to set the radar clock, and switch S2, which can be closed to provide a continuous recording of pictures. The connection to switch S1 and S2 leading to the composite picture machine is momentarily connected to ground to obtain a radar film record. As it is illustrated in the drawing of the composite picture machine (Figure 37), an emergency switch can be employed to cycle the unit at a five-minute rate. A manual push button is also located on the control panel inside the laboratory so that the operator can obtain additional radar records.

Since the dust conditions prevail within the radar van, faults frequently occur in the relay contact operation. The most frequent trouble exists in the contacts of relay CR1, which is a multiple contact counter relay. If the dust is removed from these contacts with a slip of paper, the trouble is quickly remedied. Otherwise, the operation of the radar camera control unit is very reliable.

#### The Composite Picture Machine

It is the purpose of the composite picture machine to control the action of the radar camera and the waveform analyzer camera and to provide a set of composite direction finder pictures (time exposures) exposed for different lengths of time. The radar camera control unit requires an impulse to initiate a set of three recordings. The composite picture machine provides these impulses at rates of one minute or five minutes. The waveform analyzer camera control unit requires an impulse every five minutes to take a set of regular-run pictures of 0-55 seconds duration. The composite picture machine supplies this impulse at the

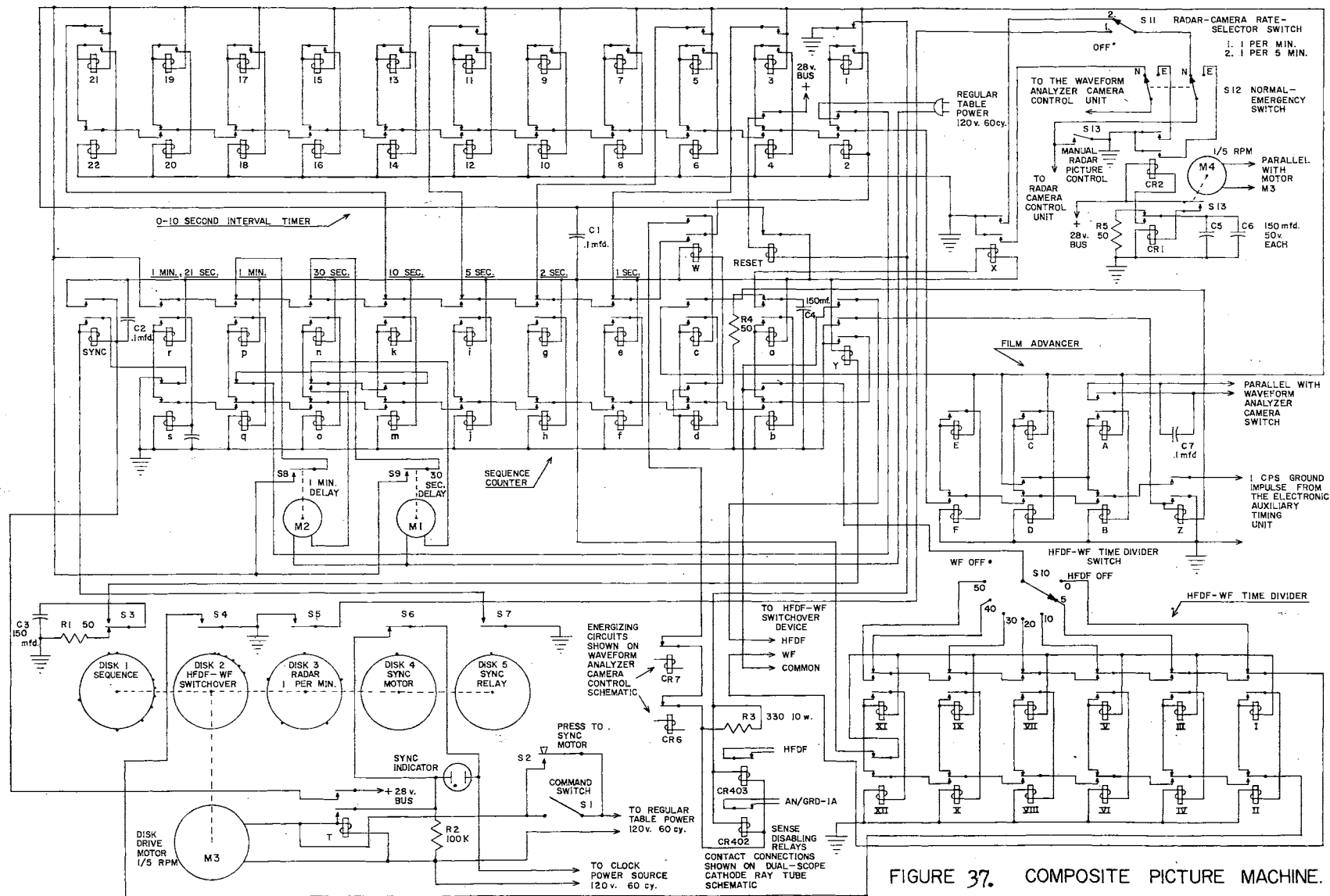


FIGURE 37. COMPOSITE PICTURE MACHINE.



beginning of each five minute period. Under control of the composite picture machine, the waveform analyzer can record, during the regular run, both direction finder and waveform pictures. Either one, or both of these modes of operation can be selected by the operator.

The composite picture machine has a five-minute cycle during which the above functions are automatically performed. The first interval of the cycle is used to obtain the regular run of records for the waveform analyzer, and the remaining four minutes of each cycle are used to record time exposures of the following duration: one second, two seconds, five seconds, ten seconds, thirty seconds, one minute and one minute and seventeen seconds.

The main controlling element of the composite picture machine consists of five disks mounted upon a single shaft and driven by a 1/5-rpm synchronous motor. Each disk has been tapped at various points about its periphery to accomodate small round-headed 2-56 machine screws. The point where each screw appears was accurately determined so that the position of each screw corresponds to an exact time during the period of rotation. The time position of each point on each disk was calculated. With the drive motor turning the disks, marks were scribed on the various disks at the corresponding time positions. After the holes were drilled and tapped and 2-56 machine screws inserted, the microswitches, which are actuated by the screw heads, were found to operate at the correct time points. The majority of the points were exact, but one or two were off about 0.5 seconds.

The five disks are shown in Figure 37. Disk 1 is the sequence impulse-generating wheel and times precisely the sequence of events during the five-minute period. Disk 2 is provided with screw heads which function

during only the first fifty seconds of the five-minute period, controlling the mode of waveform analyzer operation during the regular run of pictures. Disk 3 has screw heads to operate its microswitch at a one cycle per minute rate for use in controlling the radar camera. Disk 4 has only one screw and functions to stop the disk drive motor at a point where it can be readily synchronized with the station clock. Disk 5 is also provided with only one screw head and is used to apply 28-volt power to all relays at the beginning of each five-minute period.

The sequence of events actually begins at time  $t_0 - 0.5$  seconds, when one operates the command switch S1 to synchronize the cycle with the station clock. Switch S1 is thrown exactly 0.5 seconds before the beginning of any five-minute period. In the control circuit of the disk drive motor, relay T is connected into the microswitch of disk 4 in such a manner that the last time the unit was shut down, the disk drive motor continued to operate until the screwhead on disk 4 operated microswitch S6. The position of the disk drive shaft, corresponding to this event, represents time  $t_0 - 0.5$  seconds, and is the reason why the command switch must be thrown 0.5 seconds prior to a given five-minute period. A neon lamp NEL indicates to the operator that the disks are in the proper position to start the cycle as described above. If the neon lamp is not lit prior to the desired starting time, key S2 must be depressed. As Key S2 is depressed, relay T energizes and causes the disk drive motor to rotate to the starting position. At the proper point, disk 4 causes the drive motor to stop. The neon lamp lights and the unit can then be started at the next five minute interval.

When the command switch is operated at the start of the five-minute period, relay Y energizes and 28-volt power is applied to the sync-relay

circuit through the contacts of relay Y. Since disk 5 is in the proper position to operate switch S7, when the command switch is thrown, the sync relay energizes and applies the 28-volt power to the other relays of the unit. The sync relay is provided with a set of holding contacts and also with a reset path through the contacts of relay s.

At time  $t_0$ , the sequence impulse-generating disk 1 causes relay Y to momentarily energize. The contacts of relay Y place the HFDF-WF switchover device to the HFDF position if it is not already in that position, energizes relay Z if relay c is already energized, and applies a ground connection into relay a of the sequence counter via contacts of relay b.

Relays a and b are connected as a relay counter, and relay a and relay b energize respectively upon the application and the termination of the ground impulse from relay Y. The contacts of relay a cause the transfer relay X to energize momentarily. Relay X starts the regular run of HFDF and WF pictures in addition to starting the radar camera if the radar selector switch S11 is in the 1/5-min position. If the radar selector switch is in the 1/min position, this function is performed by disk 3. The contacts of relay b transfer the output from relay Y to relay d and connect the common lead from the HFDF-WF switchover device into the HFDF-WF time divider set of relays via switch S10.

The sequence impulse-generating disk 1 does not provide a second sequence impulse until time  $t_0 + 1.0$  minutes. Nevertheless, several events take place in the HFDF-WF time divider during this interval because of the action of disk 2. At time  $t_0 + 5$  seconds, disk 2 applies a momentary ground into the time divider and causes relays I and II to become energized. For the position of switch S10 shown, the contacts of relay I

cause the HFDF-WF switchover device to revert to the waveform mode of operation. Switch S10 can be set to other positions which give different lengths of HFDF and WF film records.

As disk 2 continues to rotate, relays III and IV energize at time  $t_0 + 10$  seconds; relays V and VI energize at time  $t_0 + 20$  seconds; relays VII and VIII energize at time  $t_0 + 30$  seconds; relays IX and X energize at time  $t_0 + 40$  seconds; and relays XI and XII energize at time  $t_0 + 50$  seconds. The arm of switch S10 can be set at any one of the switchover times indicated. The time divider circuit causes the HFDF-WF switchover device to assume the waveform mode of operation at the time set on switch S10 by the operator.

If both HFDF and WF records are desired during the regular run, the operator must set switch S10 to the position corresponding to the length of desired HFDF records and set the time arm of the waveform analyzer camera control unit to a length of time corresponding to the sum of the desired HFDF and WF recording times.

If it is desirable to take a 10-second HFDF recording and a 5-second WF recording, the selector switch S10 is set to the 10-second position and the waveform analyzer camera timer is set for a 15-second regular run. At the time  $t_0 + 10$  seconds, disk 2 will have fed two impulses into the HFDF-WF time divider and caused relays I, II, III, and IV to energize. When relay III energizes at time  $t_0 + 10$  seconds, its contacts cause the HFDF-WF switchover device to place the waveform analyzer in the waveform mode of operation. The camera records this mode of operation until time  $t_0 + 15$  seconds, at which time the timer stops the camera motor. Impulses from disk 2 continue to be fed into the HFDF-WF time divider during the interval ending at  $t_0 + 50$  seconds. They will energize relays I, II, III, IV, V, VI, VII, VIII, IX, X, XI, and XII, respectively. The contacts

of relay XII remove 28-volt power from the entire group of time divider relays and cause them to reset in preparation for the next regular run.

At time  $t_0 + 1.0$  minutes, disk 1 causes the sequence impulse relay Y to momentarily energize. The contacts of relay Y cause relay c and relay Z to energize on the application of the impulse and cause the HFDF-WF switchover device to place the waveform analyzer in the HFDF mode of operation if it is not already in this mode. The termination of the impulse results in relay d becoming energized.

It is the contacts of relay c and relay Y which cause relay Z to energize and the contacts of relay c and a set of contacts on relay Z which cause relay Z to remain energized.

The contacts of relay d transfer the output from the impulse relay Y into the next set of relays in the sequence counter and also cause relay W to energize.

Relay W energizes the sense disabling relays U and V. Relays U and V remove the patterns from the screens of the direction finder cathode-ray tubes to prevent film exposure except for the desired time interval. In the next paragraph, it will be seen that the film is advanced in preparation for the time exposure and that it is desirable not to expose the film during the advancing process. Relays U and V are de-energized for the length of time exposure and then re-energized in preparation for the next time exposure.

As relay Z energizes, a 1-cps relay, located in the electronic auxiliary timing unit, feeds 1-cycle per second ground impulses into the contacts of relay B. Relays A, B, C, D, E, and F are connected as relay counters and control the camera motor to move the film to a new position for recording the desired time exposure.

On the application of the first 1-cps impulse, relay A energizes and starts the waveform analyzer camera motor. The termination of the first 1-cps impulse results in the energizing of relay B. The application and termination of the second 1-cps impulse results in the respective energizing of relays C and D. As relay D energizes, its contacts by-pass the coil of relay A and cause relay A to de-energize, while keeping relay B energized. Relays E and F are connected to energize respectively on the application and termination of the third 1-cps impulse. They merely provide a one-second delay in order that the film motion will stop before the time exposure begins.

As relay F energizes, its contacts transfer the 1-cps impulse circuit into the contacts of relay 2 located in the 0-10 second interval timer section. The fourth 1-cps impulse causes relays 1 and 2 to energize, respectively. The contacts of relay 1 remove the ground from relays U and V and thus start the time exposure.

The fifth 1-cps impulse causes relays 3 and 4 to energize, respectively. Relay 3 by-passes the coil of relay 1 via the normally-closed contact of relay e and a contact of relay W. This action causes relay 1 to de-energize and terminate the time exposure by causing the sense disabling relays U and V to re-energize.

The contacts of relay 4 connect one terminal of the reset relay to the 28-volt bus, while the contacts of relay 1 connect the other side of the reset relay to ground. As the reset relay energizes, power is removed from all the relays of the 0-10 second interval timer, relays 1 through 2; from all relays of the film advancer, relays A through F; and from relay Z. This action resets all relays of this group in preparation for the next time exposure. Relays a, b, c, and d, in the

sequence counter remain energized.

A total time of four seconds is required to obtain the 1-second time exposure. The sequence impulse generator wheel, disk 1, is set to allow 10 seconds for this operation. Thus, the unit remains idle until time  $t_0 + 1$  minute 10 seconds, when the impulse relay is momentarily energized to start the interval for the 2-second time exposure.

The momentary operation of relay Y at time  $t_0 + 1$  minute 10 seconds causes relay Z to re-energize, insures that the HFDF-WF switchover device is in HFDF operation, and causes relays e and f in the sequence counter to energize.

The process resulting in the 2-second time exposure is the same as for the 1-second time exposure until the fifth 1-cps impulse causes relays 3 and 4 to energize. Relay 4 again connects the 28-volt bus into the reset relay, but the reset relay cannot energize until relay 1 is de-energized at the end of the time exposure. The sixth 1-cps impulse signifies the end of the 2-second time exposure, and causes relays 5 and 6 to energize. Relay 5 by-passes the coil of relay 1 via the normally-closed contacts of relay e and the contacts of relay W. This action terminates the 2-second time exposure and resets the relays in the 0-10 second interval timer, the film advancer relays, and relay Z.

A total time of five seconds is required to obtain the 2-second time exposure. The sequence impulse generator wheel, disk 1, is set to allow 10 seconds for this operation. The unit remains idle until time  $t_0 + 1$  minute 20 seconds, when the impulse relay Y is momentarily energized to start the interval for the 5-second time exposure.

At time  $t_0 + 1$  minute 20 seconds the sequence impulse-generating wheel, disk 1, causes relay Y to energize momentarily. Again relay Z is energized, the HFDF switchover unit is caused to assume the HFDF

mode of operation if it is not already in this mode, and a fourth impulse is applied to the sequence counter group of relays. The application and termination of the fourth impulse into the sequence counter results in the sequential energizing of relays g and h. A set of contacts on relay g provides the electrical path which terminates the 5-second time exposure after the record has been completed. Relay Z begins feeding 1-cps impulses into the film advancer and provides a clean strip of film for the new time exposure. After the film has advanced and the camera motor has completely stopped, 1-cps impulses then arrive at the input to the 0-10 second interval timer via contacts of relay B, D, and F.

The chain of electrical events after 1-cps pulses appear at the input to the 0-10 second interval timer is the same for each time-exposure record, except for the number of relays which must become energized before the time exposure has expired. For the 5-second time exposure, a total of five seconds must elapse from the time the first 1-cps impulse is applied to the input of the interval timer. The first 1-cps impulse to arrive at this part of the circuit causes relays 1 and 2 to become energized. Contacts on relay 1 causes the sense disabling relays to de-energize and begin the time exposure. The second 1-cps impulse into this part of the circuit is stored by relay memory action in relays 3 and 4. The third 1-cps impulse is stored in relays 5 and 6; the fourth impulse, in relays 7 and 8. This reaction continues until the sixth impulse causes relay 11 to become energized.

The arrival of the sixth impulse into the interval timer signifies the end of the 5-second time exposure, and an electrical path is established through contacts of relays 11, i, g, e, and W, which by-pass the coil of relay 1. As relay 1 de-energizes, power is applied to the



Reset relay. This in turn removes power from all interval timer relays, film advancer relays, and relay Z, resetting all of them in preparation for the next time exposure.

Although fifteen seconds are allotted for the 5-second time exposure, only eight seconds are required to complete the operation, three seconds for film advancing and five seconds for the exposure. The unit remains idle for seven seconds before the sequence impulse-generating wheel starts the 10-second time exposure.

At time  $t_0 + 1$  minute 35 seconds the sequence impulse-generating wheel momentarily energizes relay Y and starts the cycle of events which produce the 10-second time exposure. The impulse from relay Y into the sequence counter causes relays i and j to energize. Contacts on relay i establish the electrical circuit which terminates the 10-second time exposure when relay 21 becomes energized.

The first three 1-cps impulses advance the film and allow the film travel to stop completely. The fourth through the fourteenth 1-cps impulses cause the 10-second time exposure.

The fourth 1-cps impulse is applied to the 0-10 second interval timer and starts the time exposure. The fifth through the thirteenth 1-cps impulses are stored in relays 3 through 20. The fourteenth 1-cps impulse causes relay 21 to energize and complete the electrical path which by-passes the coil of relay 1. This action stops the time exposure and resets all the interval timer relays, the film advancer relays, and relay Z. The unit then remains idle until the 30-second time exposure cycle is begun.

At time  $t_0 + 1$  minute 55 seconds the sequence impulse-generating wheel momentarily energizes relay Y and starts the chain of electrical

events which result in the 30-second time exposure. The application and termination of the impulse from relay Y, which is applied to the sequence timer, results in the energizing of relays k and m. The contacts of relay k provide for the electrical path which by-passes the coil of relay 1 when the 30-second time exposure is completed.

The 30-second time exposure is the first time exposure that is essentially different from those already discussed. The first four time exposures utilize the 0-10 second interval time to determine the exposure time; the 30-second time exposure uses an electric motor-timer to set the length of time exposure. The contacts of relays m and o connect one side of the a-c line to the electric motor timer M1 and the contacts of relay 2 connect the other a-c line to the motor M1.

The first three 1-cps impulses of each time-exposure cycle are used to step up the film to an unexposed frame. It is the fourth 1-cps impulse which starts the timing of the exposure length. The application and termination of the fourth 1-cps impulse causes relays 1 and 2 to become energized. The contacts of relay 1 check to insure HFDF operation during the time exposure. The contacts of relay 2 apply the a-c power to timer motor M1. Although the 1-cps impulses continue to be counted by the 0-10 second interval timer relays, they serve no useful purpose after the fifth 1-cps impulse has energized relays 3 and 4.

Thirty seconds after relays 1 and 2 have begun the time exposure, motor M1 operates switch S9, which it controls, and completes the electrical path that by-passes the coil of relay 1. This action terminates the 30-second time exposure and resets the interval timer relays, the film advancer relays, and relay 2. When relay 2 in the interval timer resets, a-c power is removed from timer motor M1 and a spring

mechanism resets its timing ability in preparation for the next 30-second time exposure five minutes hence.

A total of thirty-five seconds is allowed for the 30-second time exposure. The timer motor M1 is accurately set to complete the time exposure with two seconds to spare before the next sequence impulse is generated by the sequence impulse-generating wheel. Actually, the sequence impulse-generating wheel and the timer motor M1 are set to synchronize as far as the allotted time is concerned. If the power frequency should change, causing a resulting change in the synchronous speed of motor M1, a similar speed change results in the synchronous motor which is used to drive the sequence wheel. A compensating action, therefore, results between the length of the time exposure and the length of time allotted for the time exposure.

At time  $t_0 + 2$  minutes 30 seconds the sequence impulse-generating wheel causes relay Y to energize momentarily. The impulse from relay Y, arriving at the sequence counter, causes relays n and o to energize. The contacts of relay n connect the contacts controlled by timer motor M2 into the circuit which by-passes the coil of relay 1 at the termination of the 1-minute time exposure. The contacts of relay o disconnect one side of the a-c line from timer motor M1 and connect it to timer motor M2 so that motor M2 begins operating as soon as relay 2 energizes.

The sequence of events for the 1-minute time exposure are identical to those just described for the 30-second time exposure. The film is advanced under control of the first three 1-cps pulses. The time exposure is begun when the fourth 1-cps pulse causes relays 1 and 2 to energize, and the time exposure is terminated when timer motor M2 causes the resetting of the interval timer relays, the film advance relays, and

relay Z.

A total time of one minute and five seconds is allowed for the events which produce the one-minute time exposure. When relay 2 de-energizes, a-c power is removed from time motor M2, and the contacts which it controls are reset in preparation for the next one-minute time exposure, five minutes hence.

At time  $t_0 + 3$  minutes 35 seconds the sequence impulse-generating wheel again causes relay Y to energize momentarily. The impulse from relay Y into the sequence counter causes relays p and q to energize. The contacts of relay p connect the electrical circuit which terminates the last time exposure. The length of the last time exposure is determined by the sequence impulse-generating wheel and is approximately one minute and twenty-one seconds in duration.

The first three 1-cps impulses cause the film to be advanced, and the fourth 1-cps impulse starts the time exposure by causing relay 1 and 2 to become energized. At time  $t_0 + 4$  minutes 50 seconds the sequence impulse-generating wheel causes relay Y to again become momentarily energized. The impulse from relay Y into the sequence counter causes relays r and s to be energized. The contacts of relay r by-pass the coil of relay 1 and cause the interval timer relays, the film advancer relays, and relay Z to reset. The contacts of relay s cause the sync relay to de-energize and remove 28-volt power from all relays in preparation for the next 5-minute cycle.

The disk drive motor M3 continues to rotate the timing disks at 1/5 rpm until time  $t_0 + 4$  minutes 59.5 seconds, which also corresponds to time  $t_0 - .5$  seconds. If the command switch S1 is open, disk 4 opens the microswitch S6 and causes relay T to de-energize and remove power from

the disk drive motor M3. This action stops the five disks at a time which corresponds to  $t_0 - .5$  seconds on the next 5-minute cycle of the composite picture machine. If the command switch is closed, relay T remains energized and disk 5 operates microswitch S7, causing the sync relay to energize and apply 28-volt power to the entire unit in preparation for the next five-minute cycle immediately to follow.

The preceding description should enable one to operate and maintain the composite picture machine. Certain features, however, were not stressed in detail and deserve additional consideration. The emergency control of data recording is obtained whenever switch S12 is thrown from the normal to the emergency position. This action on the part of the operator is warranted whenever the composite picture machine fails to function properly during the course of a storm and when repairs are being made. In the emergency operation, a small synchronous motor M4 momentarily energizes relay CR2 at a 5-minute rate. The contacts of relay CR2 function to initiate the radar and waveform analyzer cameras at a 5-minute rate.

The emergency control circuit is the original camera control that was in use until the composite picture machine was developed. Although, it does not automatically record both waveform and high frequency direction finder pictures, the operator is aware of the ability of the circuit and should take the necessary steps to insure an integrated set of data, records of both modes of waveform analyzer operation and composite pictures, if this data is required for the particular storm.

The two relays CR6 and CR7, which are in series with the sense disabling relays CR402 and CR403, serve to insure cathode-ray tube patterns on both tubes of the waveform analyzer whenever either of these relays are energized. The controls for energizing the two relays are shown in

Figure 35. Relay CR7, which energizes whenever a regular run is made, was installed to take care of the situation when the operator pressed the manual switch S2 in the waveform analyzer camera control unit and desired to override the control of the composite picture machine. Relay CR6 is energized by the manual switch S4 in Figure 35, and serves to override the control of the composite picture machine whenever switch S4 is used to take extra sets of pictures or when it is necessary to use switch S4 to take regular run pictures for periods in excess of fifty-five seconds.

#### The Optical Stroke Recorder

There is still one more camera control which also works in conjunction with the other units; it is called the optical stroke recorder. The schematic for the optical stroke recorder control circuit is shown in Figure 38. Eight small neon lamps placed on the front panel of the waveform analyzer are used to code much of the optical stroke recorder's data upon the waveform analyzer record. There is one neon lamp inside the optical stroke recorder camera and only a small amount of data can be placed on the film record with this one lamp. Therefore, it was decided that an identical lamp which would present identical information would be placed on the waveform analyzer front-panel, and that this common coded information would be used to match the two film records. Any other data pertinent to the operation of the optical stroke recorder is displayed on the remaining neon lamps which are mounted on the front panel of the waveform analyzer.

When the actual lightning discharges are photographed, the optical stroke recorder camera is orientated in the direction which appears to display the best lightning discharges. The Tri-X film used in making

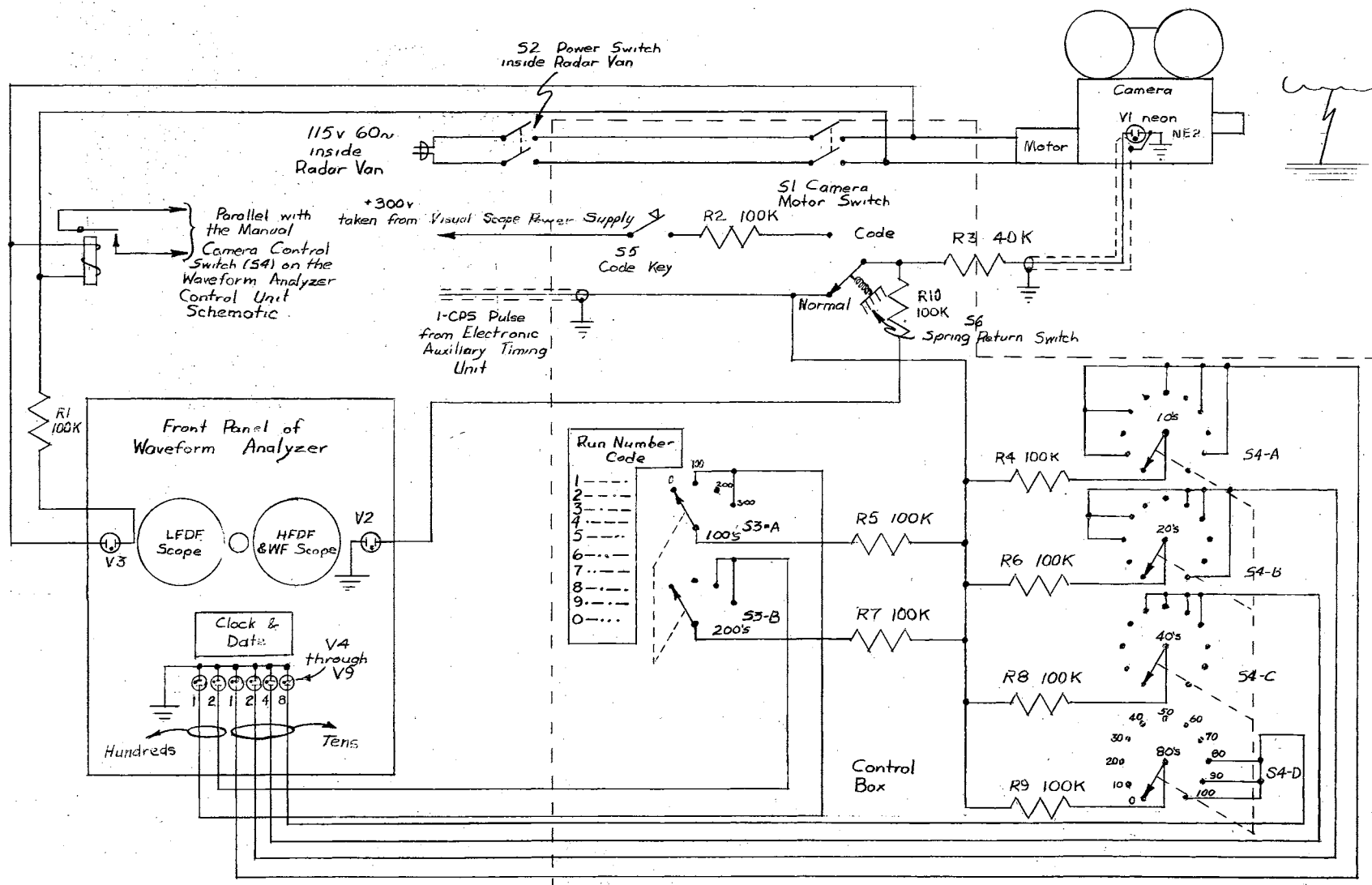


Figure 38. Circuit diagram of the Optical Stroke Recorder Control Unit.

these recordings is such a fast film that photography with this unit is limited to night use. Even on very overcast days the light is sufficient to completely fog the film. Since the camera tripod which is mounted on top of the radar van is equipped with a plastic compass card, its orientation can be accurately read. The neon code system, used to present the camera orientation on the front panel of the waveform analyzer, is capable only of indicating 10-degree intervals. For this reason, the camera has been set on the nearest 10-degree azimuth. Actually, it has been found that the lightning discharge illuminates the surrounding terrain so that the actual angle can be accurately determined from the photographed record. The operator uses switches S3 and S4 on the control box to set the azimuth toward which the camera is directed. The 1-cps impulse from the electronic auxiliary timing unit causes the proper neon bulbs, which are selected by switches S3 and S4, to flash at the rate of one cycle per second.

The six neon lamps used for azimuth coding purposes are directly beneath the clock on the waveform analyzer front panel. The first two neon lamps use a binary code to show hundreds of degrees. When both lamps are lighted they represent 300°; the left lamp represents 100° and the right lamp 200°. When neither lamp is lighted it indicates that the azimuth is between 0 and 90 degrees, zero-hundreds. The third through the sixth neon lamps employ a binary code to represent the number of 10-degree intervals, the lamps standing for 10, 20, 40, and 80 degrees, respectively. A combination of the last four lamps must be lighted to represent 30, 50, 60, 70, and 90 degrees. For example, if the angle 260° is to be represented, the second, fourth, and fifth neon lamps must be lighted.



After the operator has orientated the camera and set the azimuth code by means of switches S3 and S4, he can start the camera motor by means of switch S1. A pair of wires connect across the motor terminals and also feed this 115v - 60 cycle power into the tornado laboratory. Inside the laboratory, relay CR75 becomes energized and overrides the composite picture machine and starts the waveform analyzer camera motor. The 115v - 60 cycle power also causes a neon indicator lamp just to the left of the low frequency direction finder cathode-ray tube to be continually lighted during the entire camera run. As soon as the waveform analyzer camera becomes operative, an indication of this fact is recorded on the paper-tape record of the HFDF-counter. It serves to aid the analyst in correlating the two film records.

Immediately following the start of the recording, the operator moves switch S6 to the Code position and uses the Code Key S5 to place the run-number code on both film records. With switch S6 in the Normal position, 1-cps impulses are fed into the single neon lamp V1 inside the optical recorder camera, and also into the neon lamp V2 inside the laboratory just to the right of the HFDF cathode-ray tube on the waveform analyzer front panel. As switch S6 is placed in the Code position, the run-number code is made to appear on both these neon lamps simultaneously to aid in matching film records during analysis. A four-character code was devised so that an inexperienced code operator could record a two digit run number without difficulty. When the run is complete, the operator uses switch S1 to stop camera motors and terminate the run.

It has been found helpful for the operator to have a log book in order to keep track of how many runs are made at a specific angle and

to dispense with the run-number code except when the camera is orientated to a new direction. The operator is left to his own discretion concerning when runs should be made and how many should be made. Usually, the operator can observe the relatively periodic behavior of certain cloud-to-ground discharges and anticipate a subsequent stroke. If the operator can successfully anticipate strokes, he can obtain a great deal of data on a small amount of film by not starting the camera until just prior to the expected lightning discharge.

## CHAPTER VII

### ANALYSIS OF RESULTS

At the beginning of the 1956 tornado season, it was not known exactly how the completed tracking system would respond to severe storms. The preliminary tests made with the HFDF counter indicated that increasing count trends were produced by storms whose intensity was increasing. It was not known to what degree the count would increase when a tornadic condition was approaching. A storm intensity index would have to be established by trial on a multitude of storms.

After several months of operation by the tornado laboratory at the college, the Air Weather Service was able to establish a storm intensity index. It appeared that rapid count increases with maximum counts approaching 20 or more pips, electrical discharges, per second were followed by reports of tornadic activity in the area under consideration.

Although the devastating tornado at Drumright early in the 1956 tornado season failed to register on the laboratory equipment, a high percentage of verifications was established. During the first few months of this tornado season, there was an 87% correlation between tornadic activity and counter readings of 20 or more pips per second. By the end of the tornado season this correlation had approached 90%.

Although it is the purpose of the recording equipment to obtain data for future analysis, the operator can also observe the equipment and determine the immediate condition of a storm. Since an entire dissertation could be devoted to the complete analysis of a single storm, only a few

examples are included here to indicate the capability of the system. A single phase of a complete storm is presented in which the equipment indicated "tornado," and yet there was no immediate confirmation. It was nearly six weeks after the storm that a Nowata, Oklahoma paper was found that bore witness to the fact that a tornado had existed in the area under observation. The following topic relates how this storm was tracked and evaluated.

#### Watova Tornado

On May 23, 1956, the tornado laboratory was in action recording the progress of a storm system. It appeared that the storm might become active during the noon hour, and for this reason the equipment was allowed to operate automatically throughout this period. That the suspected activity did not develop during this interval was immediately recognized by viewing the paper tape record for the HFDF counter. There had been activity, but not of sufficient intensity to warrant concern.

About 1400 CST (2:00 p.m.) the activity developed with great speed. The HFDF counter record for 1348 CST (Figure 39) indicated a maximum count of 7 pips per second at an azimuth of  $62^{\circ}$ . There was a single radar echo at a distance 63 nautical miles from the laboratory and at this particular azimuth. The 1400 CST HFDF counter record showed a count so high that the indicator pegged on the 0-10 scale. The 0-10 scale is capable of indicating greater than 10, even though this range is normally used when the count is below 10 pips per second. When the instrument pegs on this range, the count is in excess of 15 pips per second. Whenever the count exceeds 10 pips per second, the operator is instructed to switch to the 0-30 scale. During the 1400 CST scan, the counter was

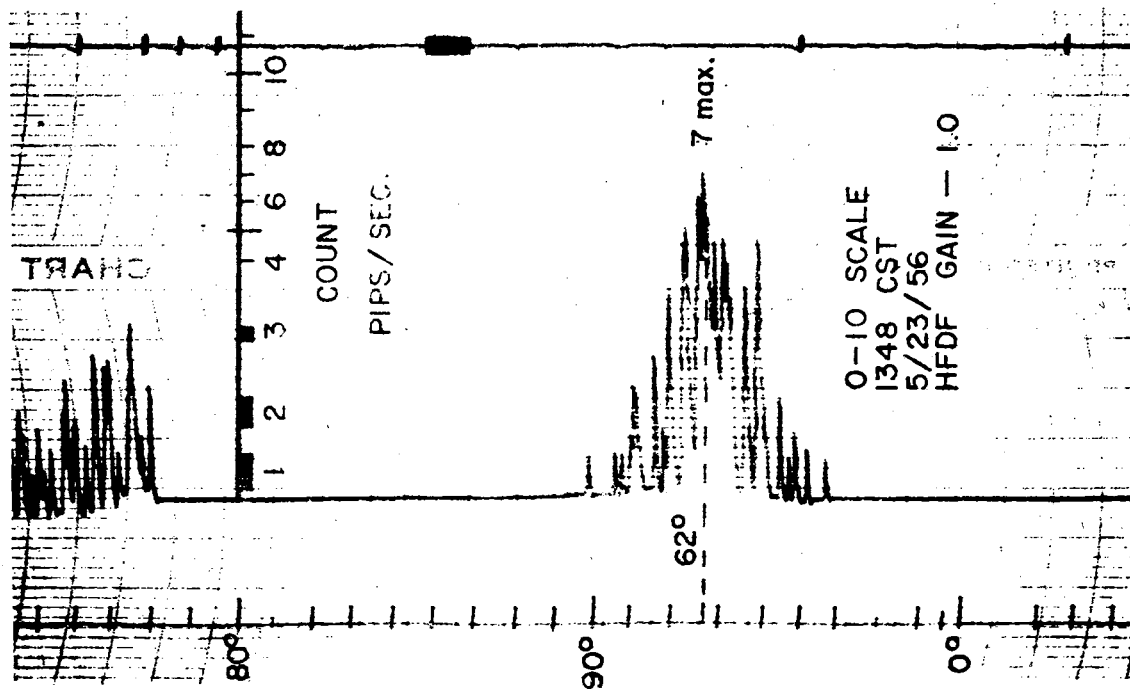


Figure 39. HFDF counter record, 1348 CST, May 23, 1956.

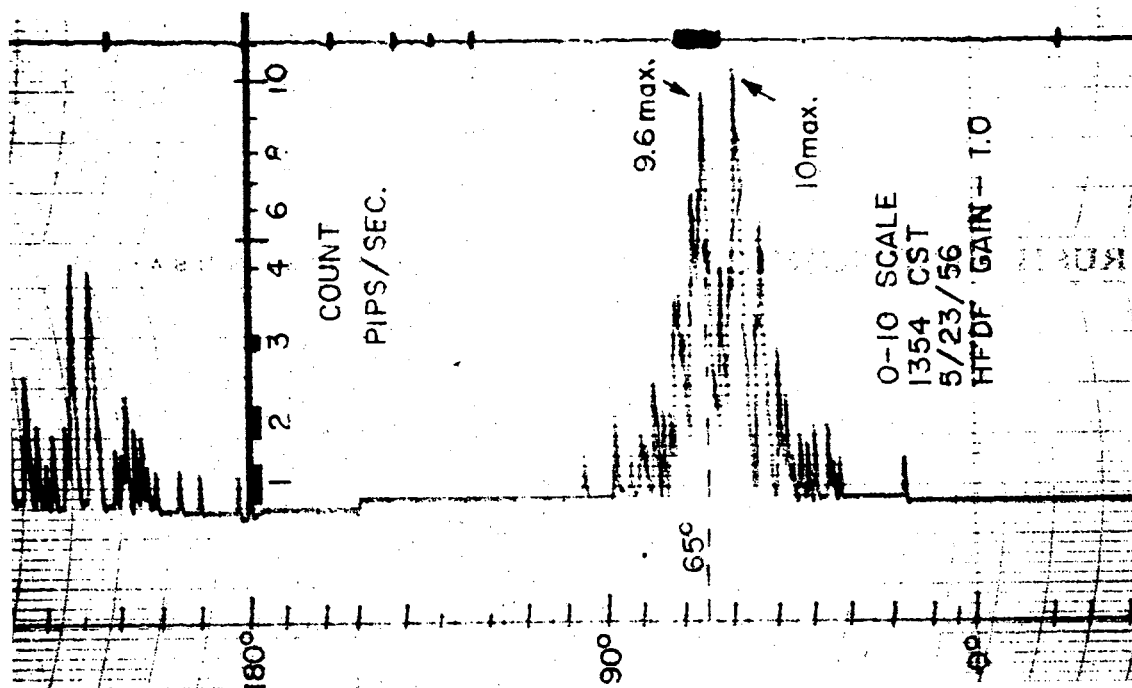


Figure 40. HFDF counter record, 1354 CST, May 23, 1956.

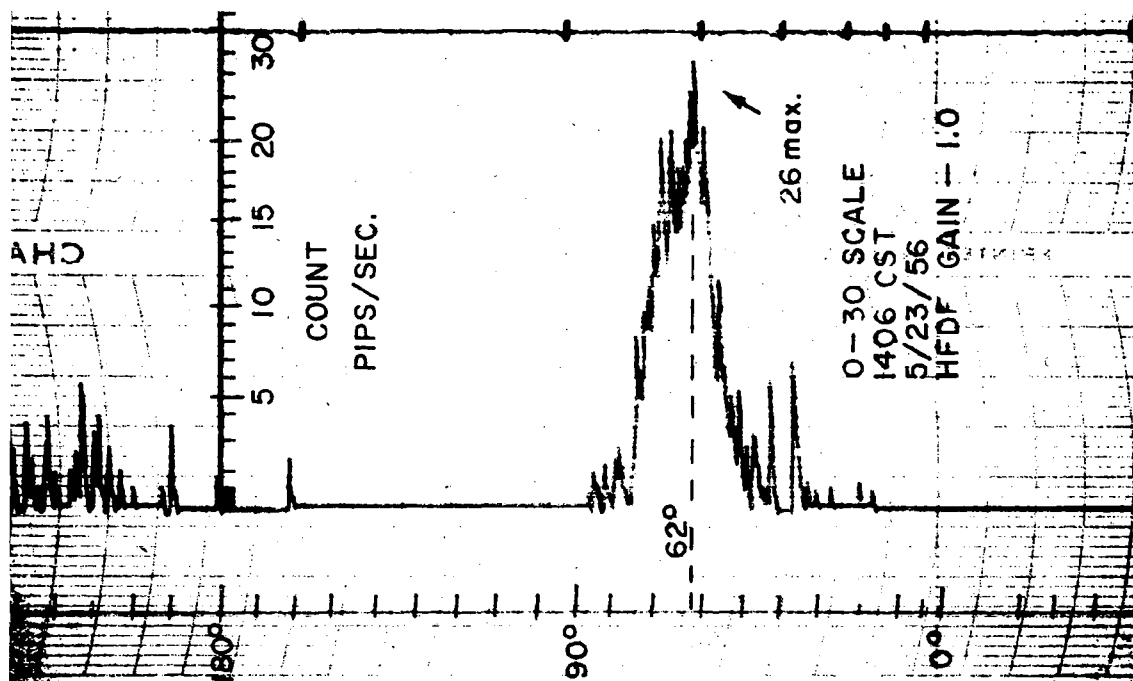


Figure 41. HFDF counter record, 1406 CST, May 23, 1956.

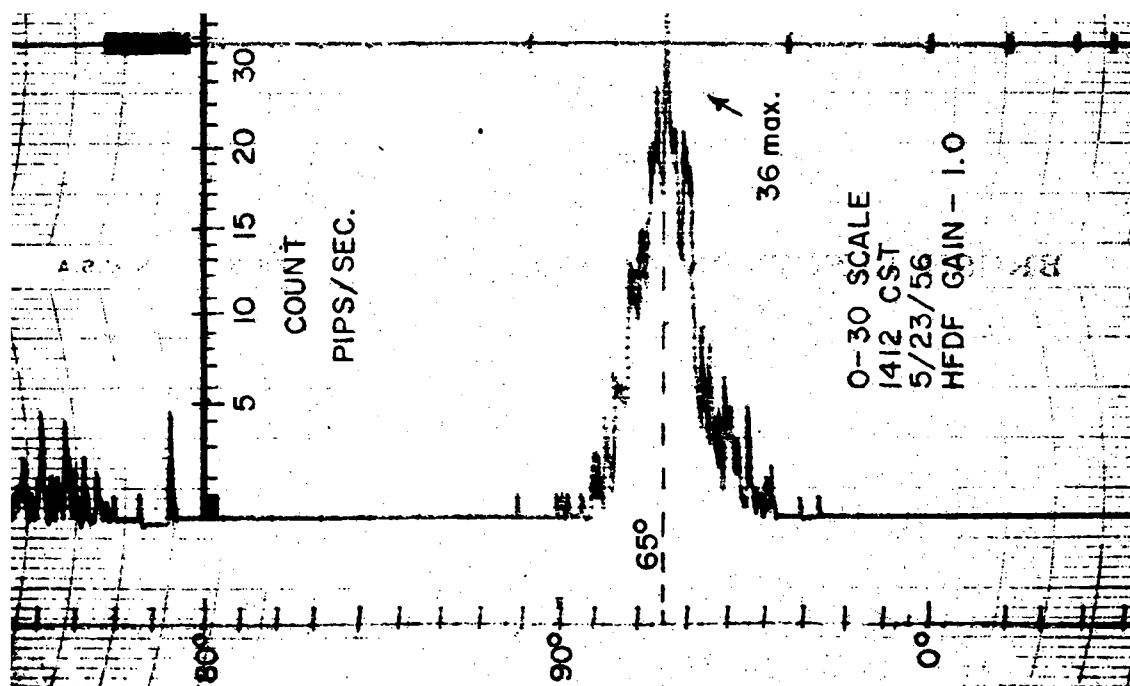


Figure 42. HFDF counter record, 1412 CST, May 23, 1956.

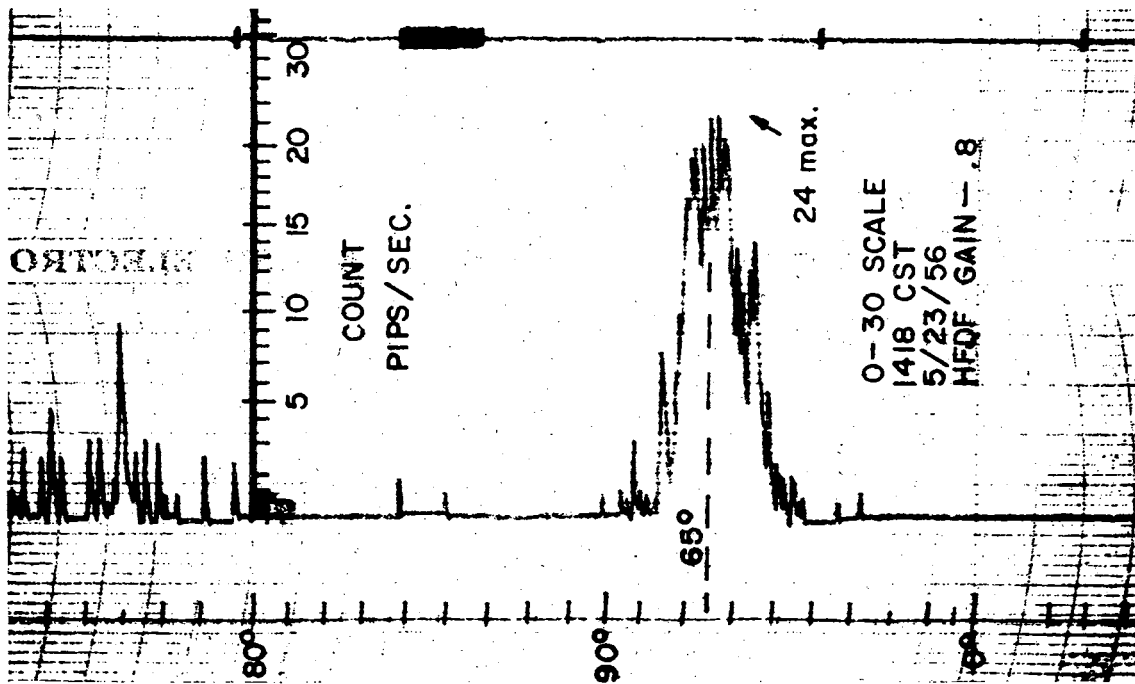


Figure 43. HFDF counter record, 1418 CST, May 23, 1956.

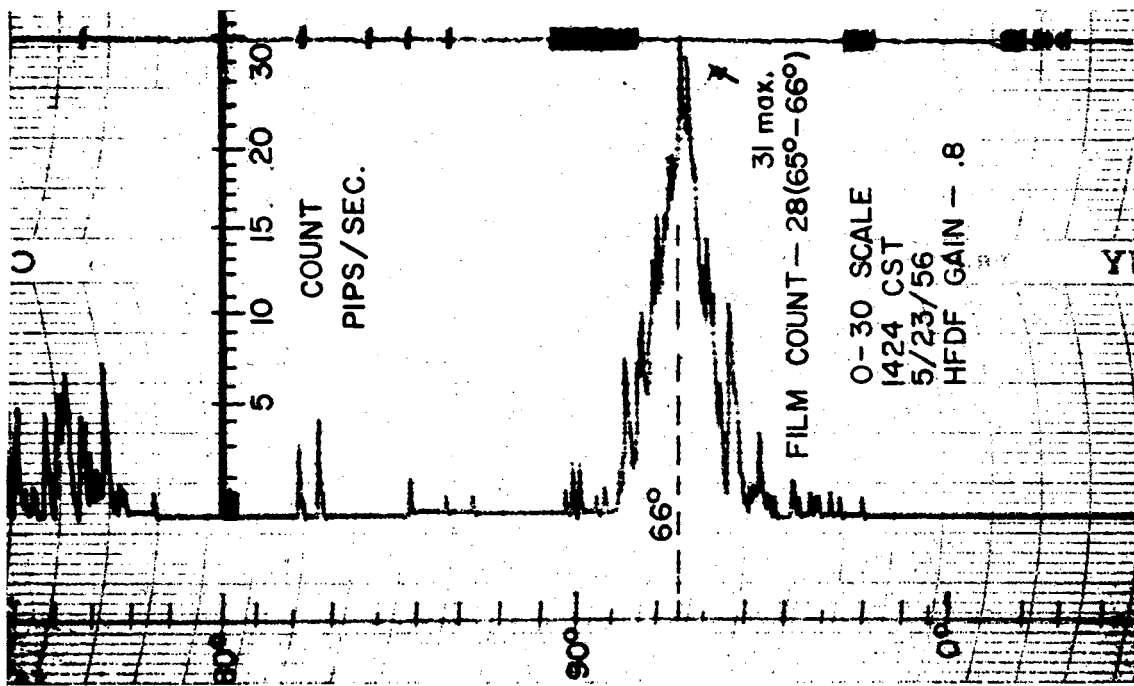


Figure 44. HFDF counter record, 1424 CST, May 23, 1956.

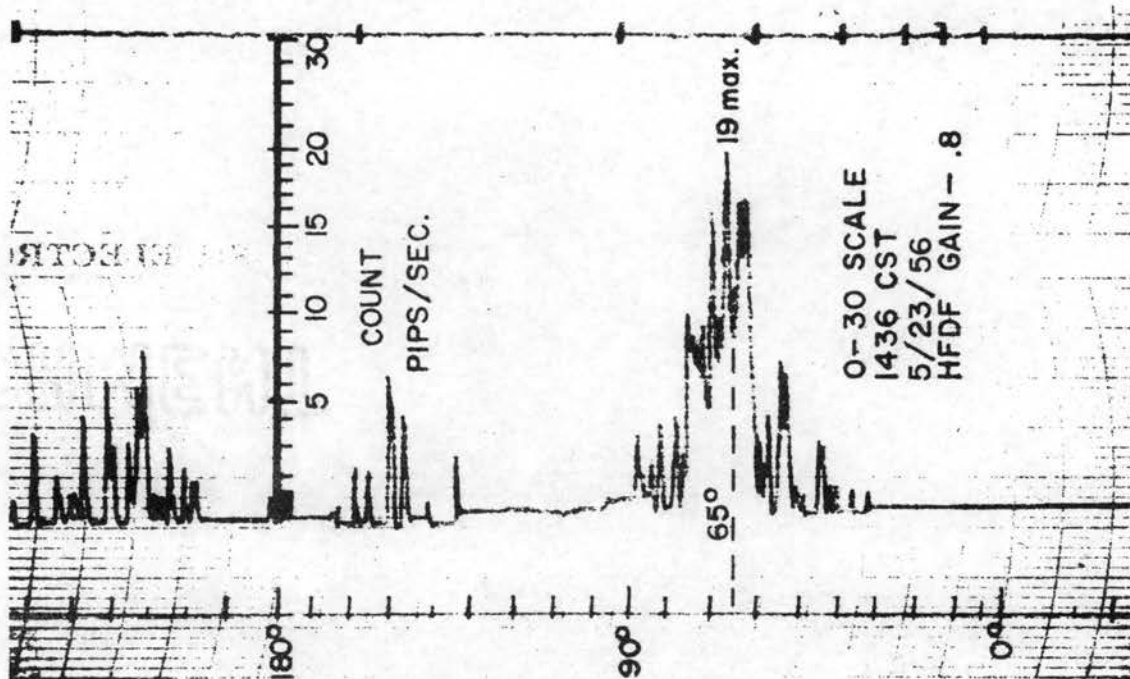


Figure 45. HFDF counter record, 1436 CST, May 23, 1956.

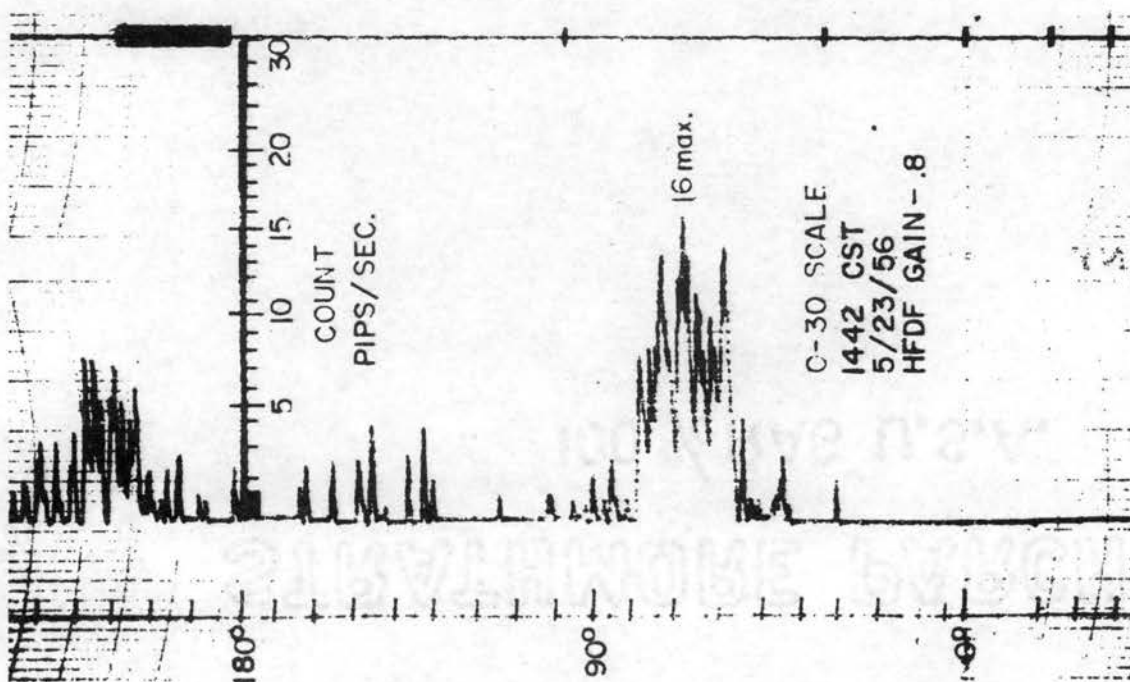


Figure 46. HFDF counter record, 1442 CST, May 23, 1956.



5-23-56

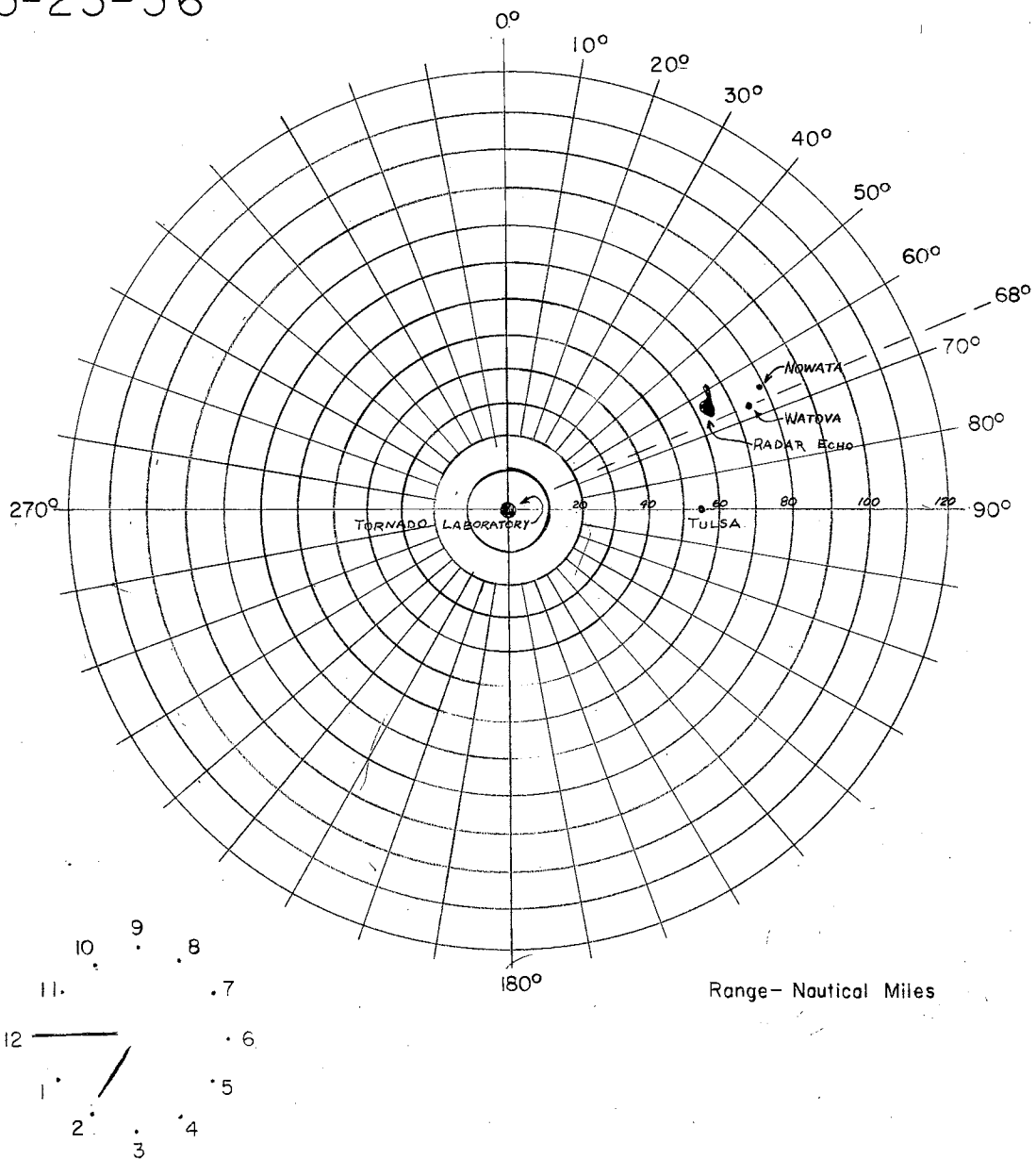


Figure 47. Sketch of radar presentation, 1400 CST, 5/23/56.

5-23-56

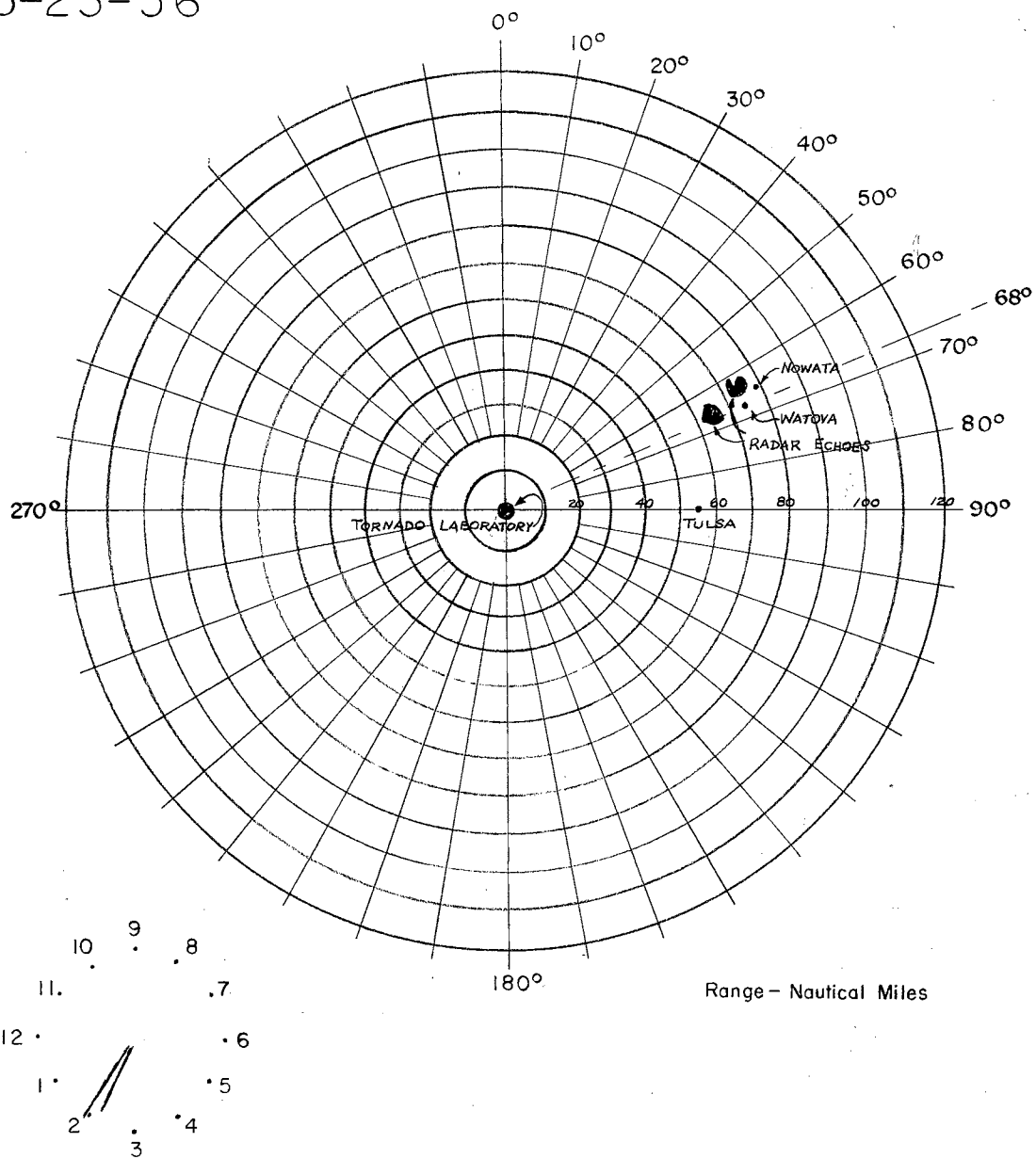


Figure 48. Sketch of radar presentation, 1410 CST, 5/23/56.

5-23-56

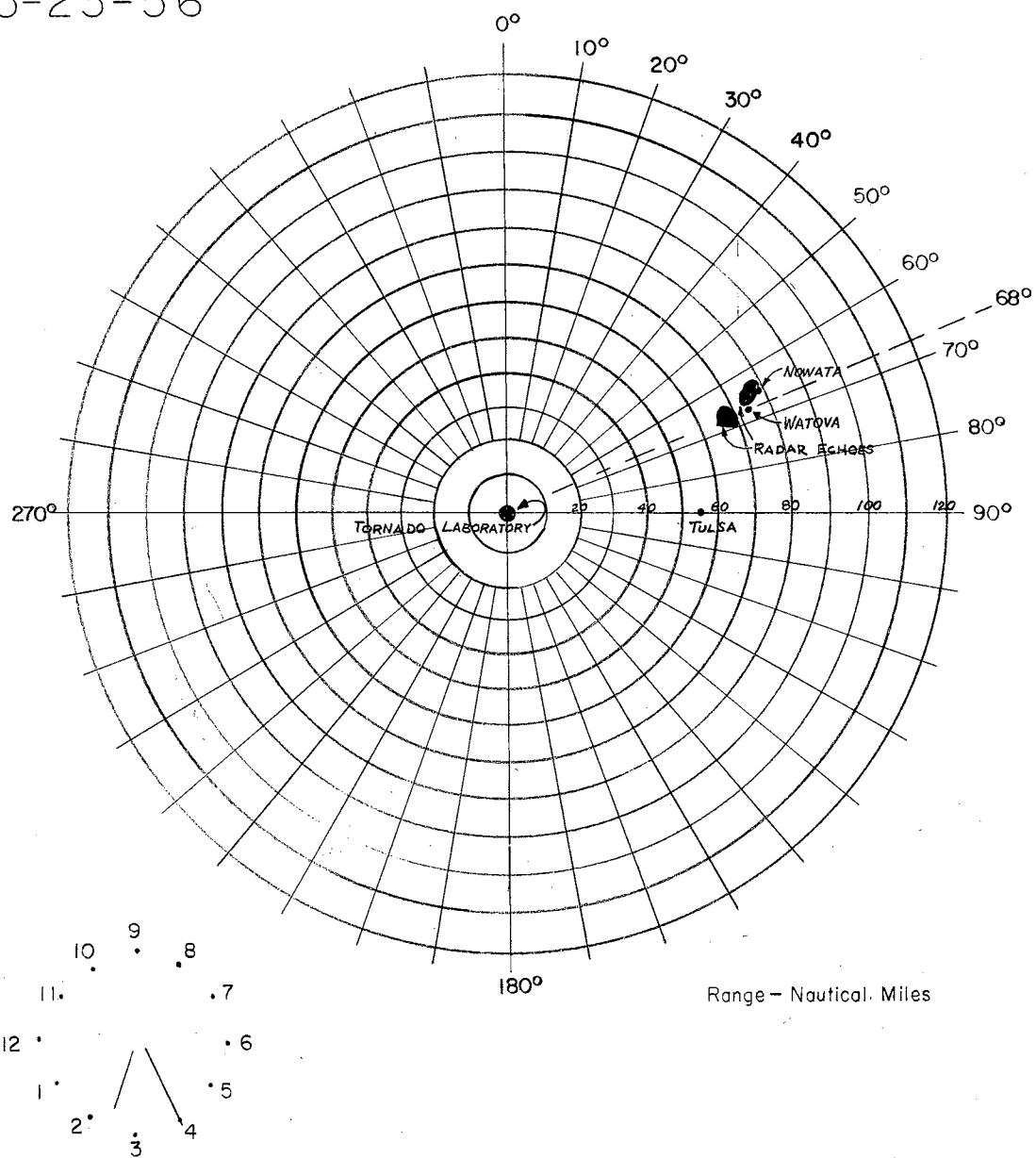


Figure 49. Sketch of radar presentation, 1420 CST, 5/23/56.

5-23-56

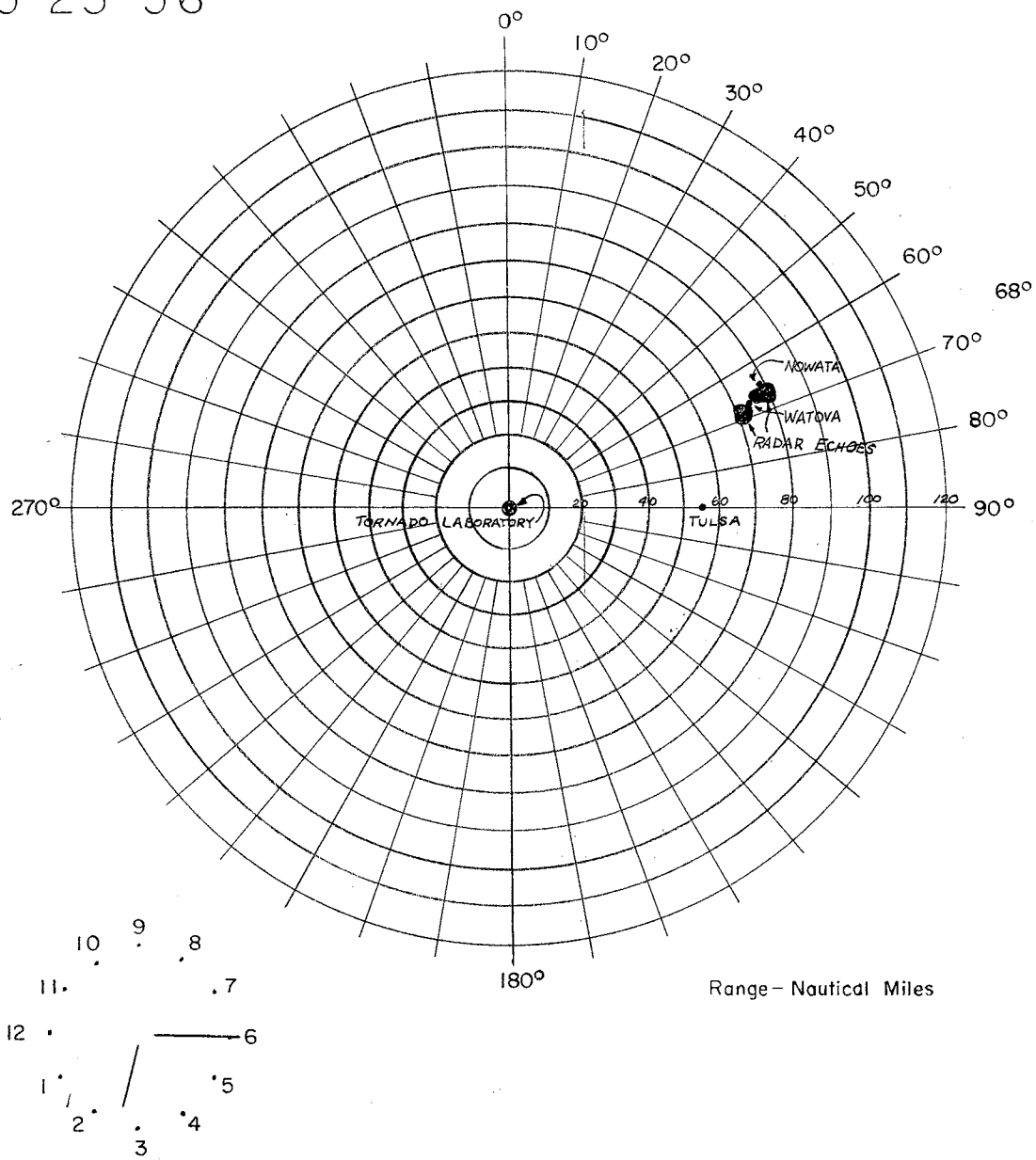


Figure 50. Sketch of radar presentation, 1430 CST, 5/23/56.

switched to the 0-30 range.

The 1406 CST HFDF record gave the maximum count as 26 pips per second at 62°. The radar (Figures 47 through 50) revealed that the echo was moving in an easterly direction in the vicinity of some 30 nautical miles NNE of Tulsa. Experience gained during previous months indicated that this condition was tornadic. The information concerning the latest development of the storm was relayed by direct phone line to Air Weather Service (AWS) in Kansas City. When the people at the Weather Bureau were notified of the sferic count from this storm center, they issued a tornado alert for the area within a 30-mile radius of a point 20 miles NE of Tulsa.

The storm progressed and developed to a most severe stage by 1424 CST. The HFDF counter records (Figures 39 through 41) indicate how the storm intensity increased from a trifling 7 pips per second at 1348 CST to an alarming 36 pips per second at 1412 CST. The records illustrated in Figures 42 through 46 show that the storm remained intense until about 1430 CST and then began to drop to a level that was not too severe. At 1448 CST the count was reasonably high and was still considered dangerous, but subsequent records indicated that the storm had subsided and was not dangerous.

The only towns near the most active storm center was Nowata and Watova, Oklahoma. A condition developed which surely was tornadic in nature, and yet no word had been announced to confirm the story told by the tracking equipment. Another storm developed south of the station and ultimately culminated in a tornadic indication near Midwest City, Oklahoma. The confirmation of this tornado was received the same afternoon.

Operators reasoned that perhaps the equipment had been wrong about the condition at Watova, Oklahoma. It had been wrong before in a certain percentage of the cases, but not so dead wrong. In other cases, a tornado would occur which did not give a high enough count, but this count was certainly adequate. The solution came to light in the form of a report from the Air Weather Service. These answers first appear in the station log of June 29, 1956. The log contains the information received by phone from Capt. Edwin B. Dickson of the AWS in Kansas City. A complete record is presented in the Air Weather Service final report for 1956.

The following material is taken directly from the final report compiled after the tornado season of 1956<sup>1</sup>.

Issuance of severe weather advisories for small areas (radius of 30 miles or less from a point) based on sferics readings appears feasible for many "favorable" situations. Seldom, if ever, during the year did a severe storm occur within a 100 mile radius of Oklahoma A & M College without detection by the 150 kc sferics set at that location. On the other hand, sferics advisories based on 10 kc sferics readings can be issued only in the limited number of situations where suitable readings are obtained.

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 indicate 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.

The 10 kc sferics readings are quite erratic. For example, the sferics may read strong counts on tornadic activity in a certain area one day and read very weakly on activity just as severe in the same

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<sup>1</sup>FINAL REPORT; PHASE 1956; PROJECT TORNADO - SFERICS; Conducted By: 6th Weather Squadron (Mobile), Lt. Col. Bernard Pusin, Commander; Dept. 25, 6th Weather Squadron (Mobile), Major Robert C. Miller, Commander; dated 31 October 1956.

area the following day.

Sferics tornado advisories were transmitted for the first time during this season. Good three - or four-station fixes were required with sferics counts of 15 pips per second or greater from the Oklahoma A & M station and/or long bursts reported on the fix by one or more of the AWS stations. A total of 21 tornado advisories were transmitted in 17 storm situations (on three occasions two or more advisories were issued for the same area on successive runs). Verification data was not available for one situation, since the fix was in the Gulf of Mexico. Nine of the 16 verifiable sferics advisories predicting tornadic development in specific areas were considered verified. Several hailstorms and/or windstorms occurred in 6 or the 7 situations where tornadoes were not reported. One advisory was issued on an erroneous fix.

It is believed that significant improvement can be made both in quantity and quality of sferics tornado advisories issued in 1957. This can be achieved by additional experience gained in operation of the sferic counter at Oklahoma A & M College, availability of new sferics equipment operating at a higher frequency, and realization of the great operational potential of the sferics telemetering equipment.

On 23 May 1956, 1400 CST, the sferics count at Oklahoma A & M suddenly increased to 28 pips per second at 063 degrees. Using data from the AWS stations, a four-station fix was located 20 nautical miles north of Tulsa, Oklahoma. At 1430 CST the count was 20 pips per second and the fix was 20 miles northeast of Tulsa. A sferics tornado advisory transmitted at 1439 CST stated, "Very strong sferics 20 N of Tulsa. Possible tornadic development indicated". The Weather Bureau SELS unit issued a forecast at 1410 CST which stated, "Intense sferics and rapidly increasing radar echo 20 NNE of Tulsa, Oklahoma moving southeast. Indicated isolated severe thunderstorm with possibility of tornado from current time until 1730 CST in an area 30 miles radius of a point 20 miles northeast of Tulsa.

About two weeks later a newspaper clipping from Nowata, Oklahoma stated that a tornado had cut a path through brush and woodland on a ranch 25 miles northeast of Tulsa between 2:00 P.M. and 3:00 P.M.

Another interesting case developed on the same afternoon. A small storm between Oklahoma City and Norman, Oklahoma intensified and the sferics count at Oklahoma A & M increased to 18 pips per second at 1500 CST on this storm. Slow movement northward, between 5 and 10 knots was indicated. It was considered a threat to Tinker AFB. The Weather Bureau RADU unit at Kansas City called the Oklahoma City radar reported that the echo had a hole in it.

A sferics tornado advisory was not transmitted, however, the Tinker AFB weather station was alerted concerning the severe nature of the storm. At 1545 CST a funnel dipped momentarily out of the base of the clouds over Midwest City, Oklahoma, adjacent to Tinker AFB. The sferics count at Oklahoma A & M did not exceed 19 pips per second. If the sferics rate had increased to the value read on the Tulsa storm, the Tinker AFB - Midwest City area might have been in serious trouble.

A further analysis of the HFDF film record of the Watova storm revealed the accuracy of the equipment indications. A set of film record whose times closely correspond to the times on the counter records were selected and certain one-second intervals were evaluated.

A group of photographs made from the HFDF film record are presented (Figures 51 through 57) to indicate the extent of the HFDF activity during the tornadic interval. Each photograph represents less than one second of the film record. The HFDF record appears below the clock and the directional pips are represented by the light lines extending in various directions from the axis of travel. It must be remembered that the film is in constant motion while the HFDF pattern is being displayed on the cathode-ray tube screen. Thus, a center line that corresponds to the origin of the presentation appears as a result of film motion. Increasing time is to the left. The clock and date card are momentarily illuminated at a one-cycle per second rate and appear at regular intervals along the film. The 35 mm film travels approximately two inches per second.

On the HFDF record, north is to the right, east to the bottom, south to the left, and west is the top. The bright line to the right of the clock is a code indication revealing that the cardinal points are presented in this manner. The majority of the activity in Figure 51 is at  $62^{\circ}$  where  $0^{\circ}$  represents due north. The AN/GRD-1A record appears above the clock, but the unit was undergoing modifications at the time of the Watova storm and did not present useful information except to illustrate the relative activity of the two units.

In evaluating the film records one particularly notes the erratic spheric activity. The radiation appears in bursts which repeat



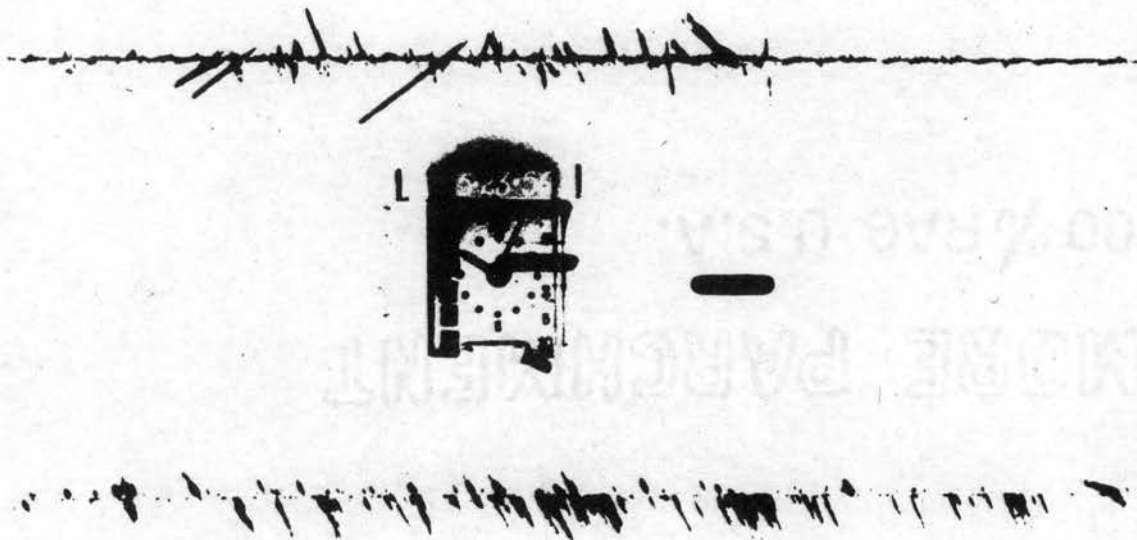


Figure 51. HFDF film record, 1350 CST, May 23, 1956.

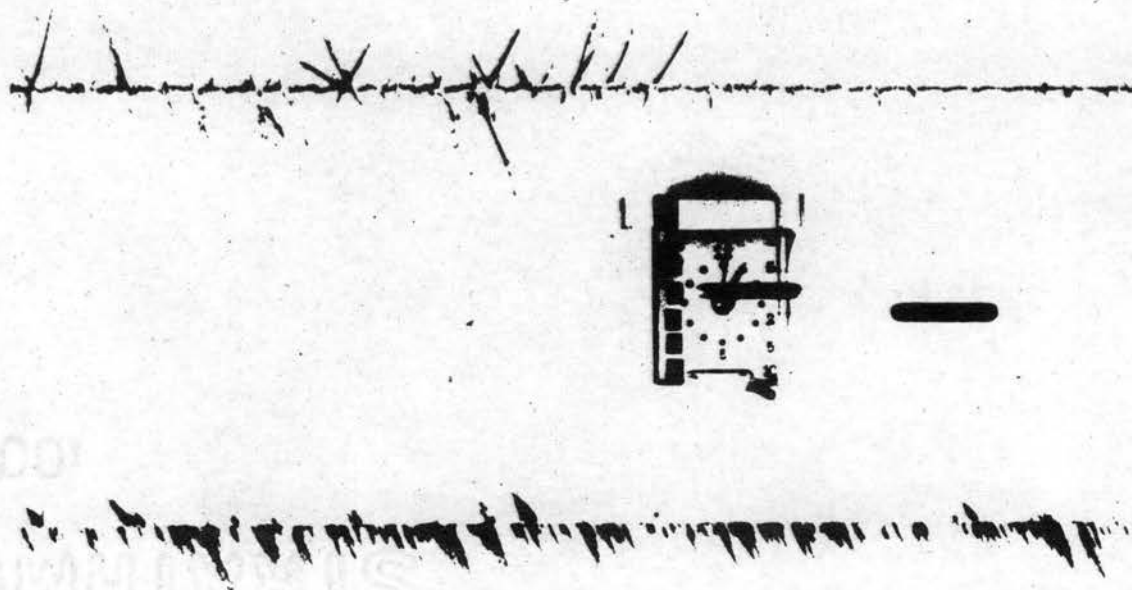


Figure 52. HFDF film record, 1405 CST, May 23, 1956.



Figure 53. HFDF film record, 1410 CST, May 23, 1956.

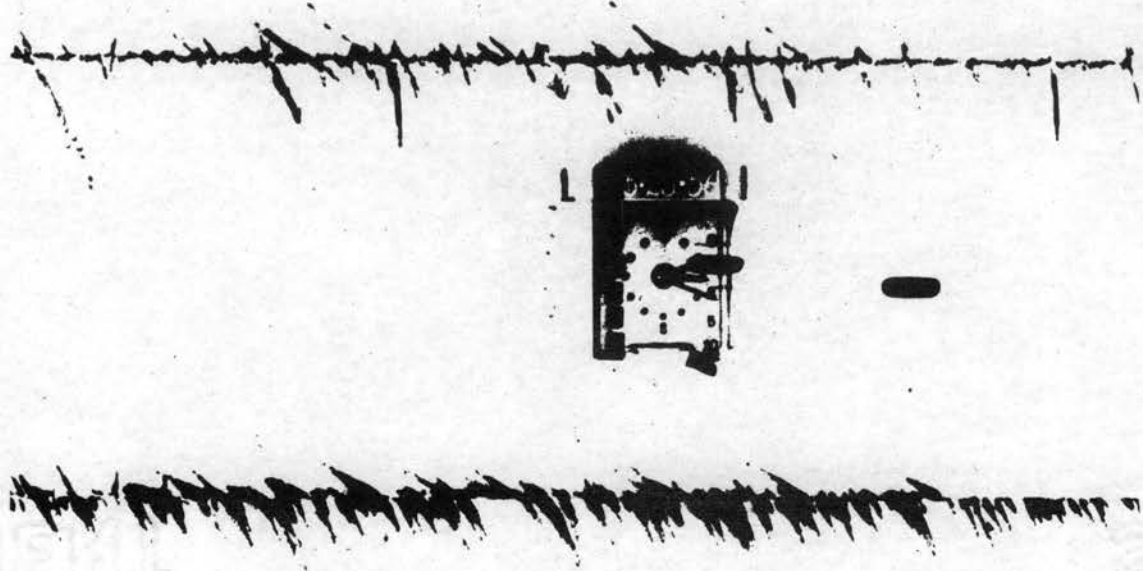


Figure 54. HFDF film record, 1415 CST, May 23, 1956.

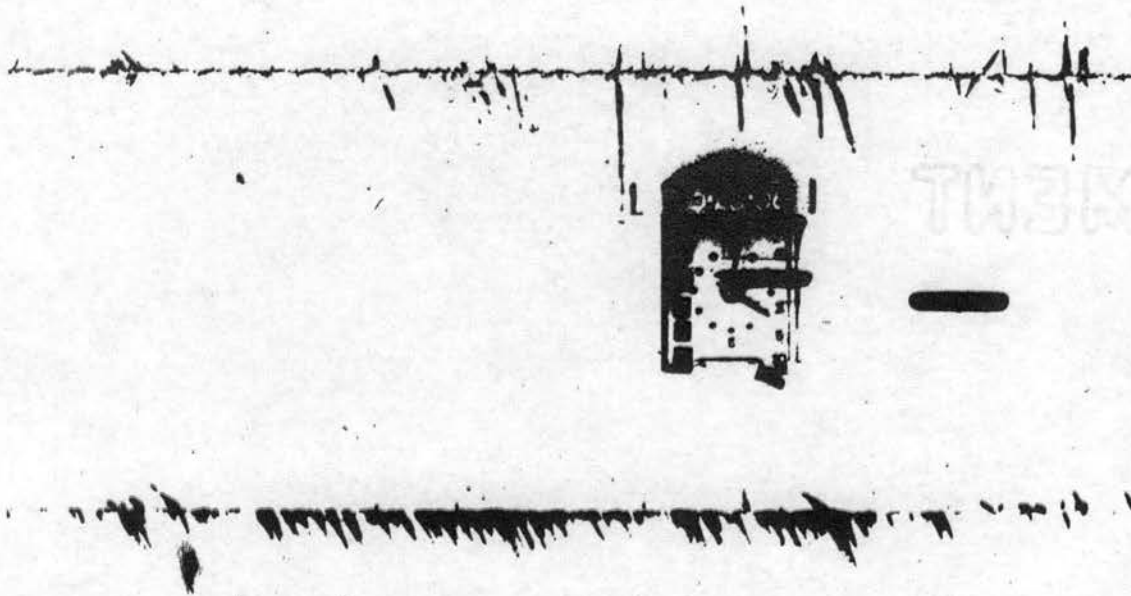


Figure 55. HFDF film record, 1420 CST, May 23, 1956.



Figure 56. HFDF film record, 1425 CST, May 23, 1956.

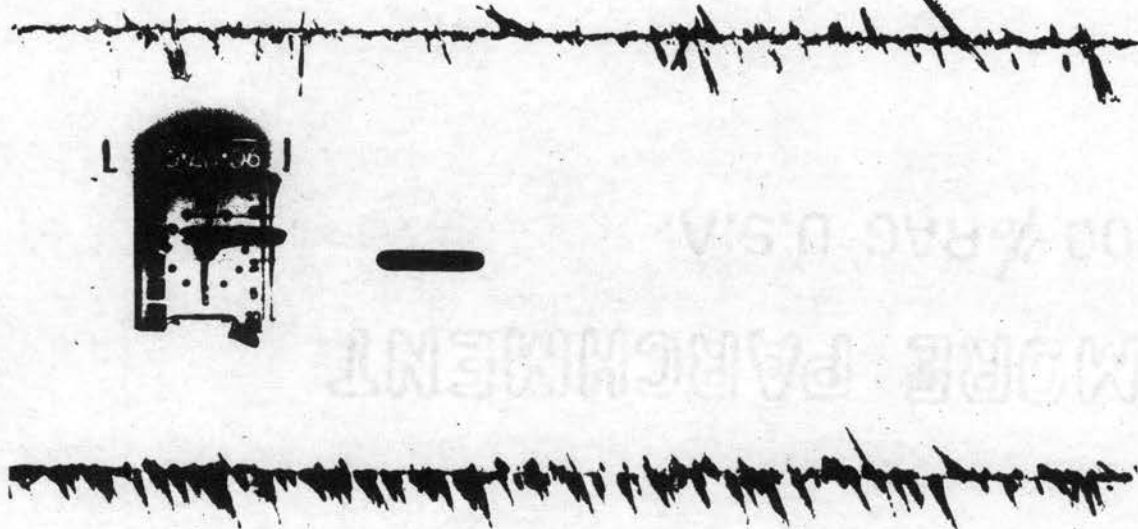


Figure 57. HFDF film record, 1430 CST, May 23, 1956.

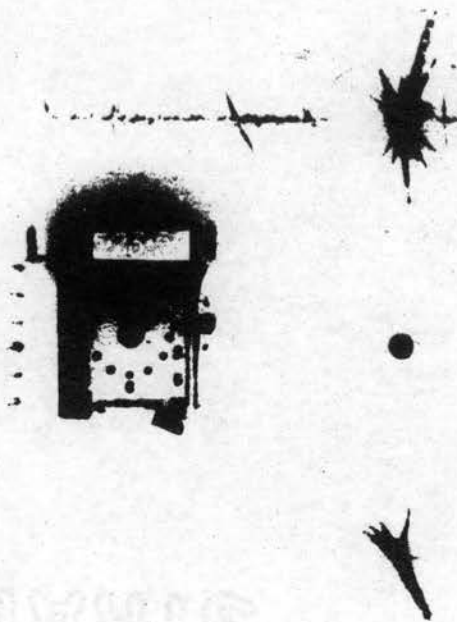


Figure 58. HFDF film record, 1355 CST, May 23, 1956.  
Record of one-second time exposure or composite picture.

rapidly. Each burst may contain from 50 to more than a 100 directional pips and may last from less than a second to several seconds. Each of the photographs represents a portion of a long burst with one of the complete shorter bursts being shown in Figure 55. From the seven brief records shown in Figures 51 through 57, one observes that the activity in the  $60^{\circ} - 70^{\circ}$  region noticeably increases as was indicated by the HFDF counter records. In an attempt to verify the HFDF counter records, several of the film records were used in preparing a count of the directional pips.

The six one-second intervals chosen were sketched and all of the directional pips counted were tabulated. The sketches (Figures 59 through 64) are presented to show the details of the count and how the directional pips are numbered. Each of these sketches uses a reference line drawn parallel to the axis to act as a division between directional pips too short to be counted and those that have sufficient length. This reference line is used to correspond to the fact that a directional pip must be of sufficient amplitude to be observed by the HFDF counter. It is obvious in some of the sketches that there exists a large number of directional pips which are not counted. Should the large count values now experienced be amazing to the reader, just consider how much larger the count would be if all of the directional pips could be observed by the counter. The thunderstorm is a tremendous source of electromagnetic radiation.

The directional pips in each sketch are assigned a letter and a number designation, and the results of the count are tabulated in Tables I and II. In order that the data from the count could be presented in a form similar to that displayed by the HFDF counter, the tabulated data was

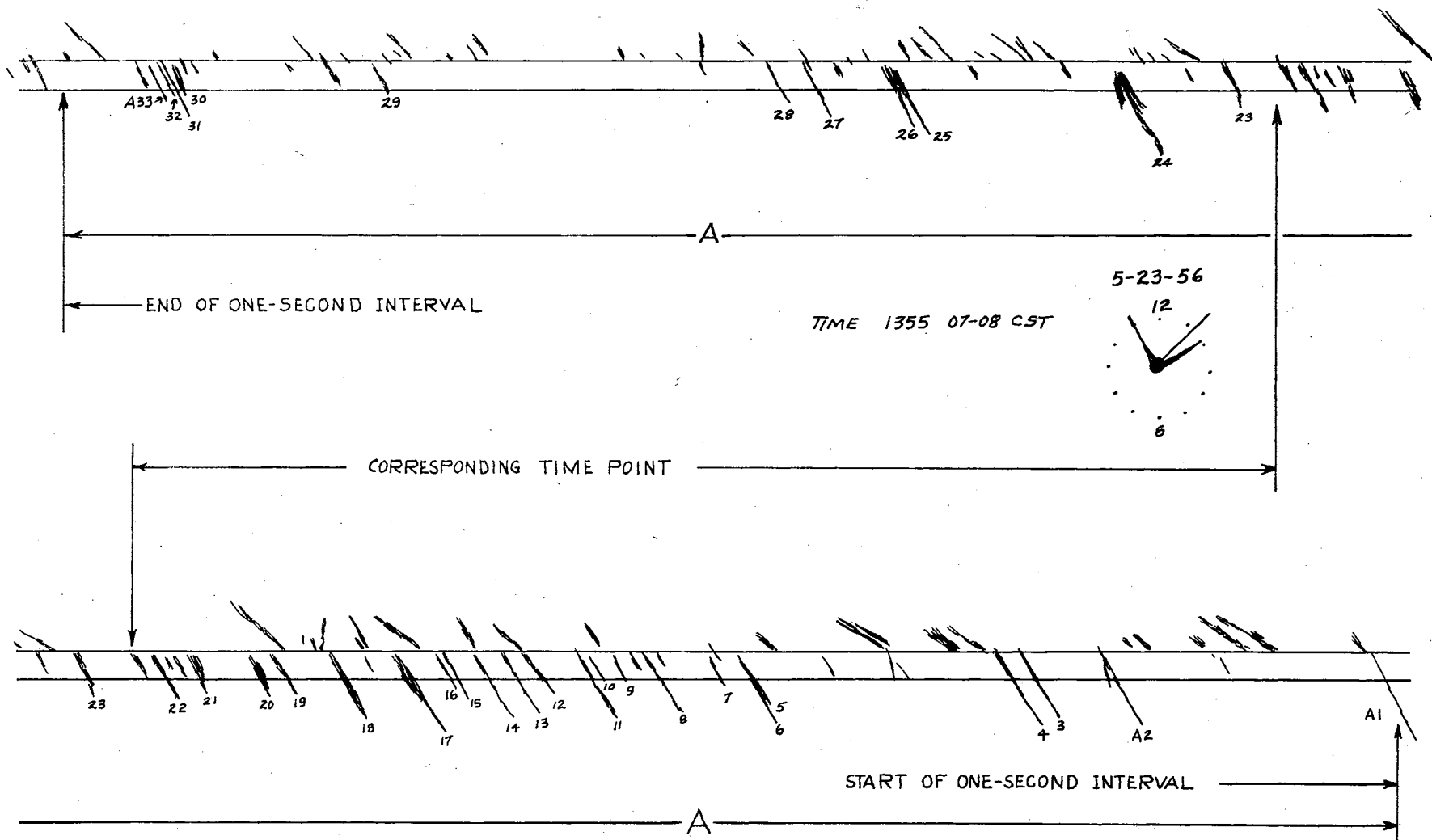


Figure 59. Sketch of the HFDF film record, 1355 07-08 CST, May 23, 1956.



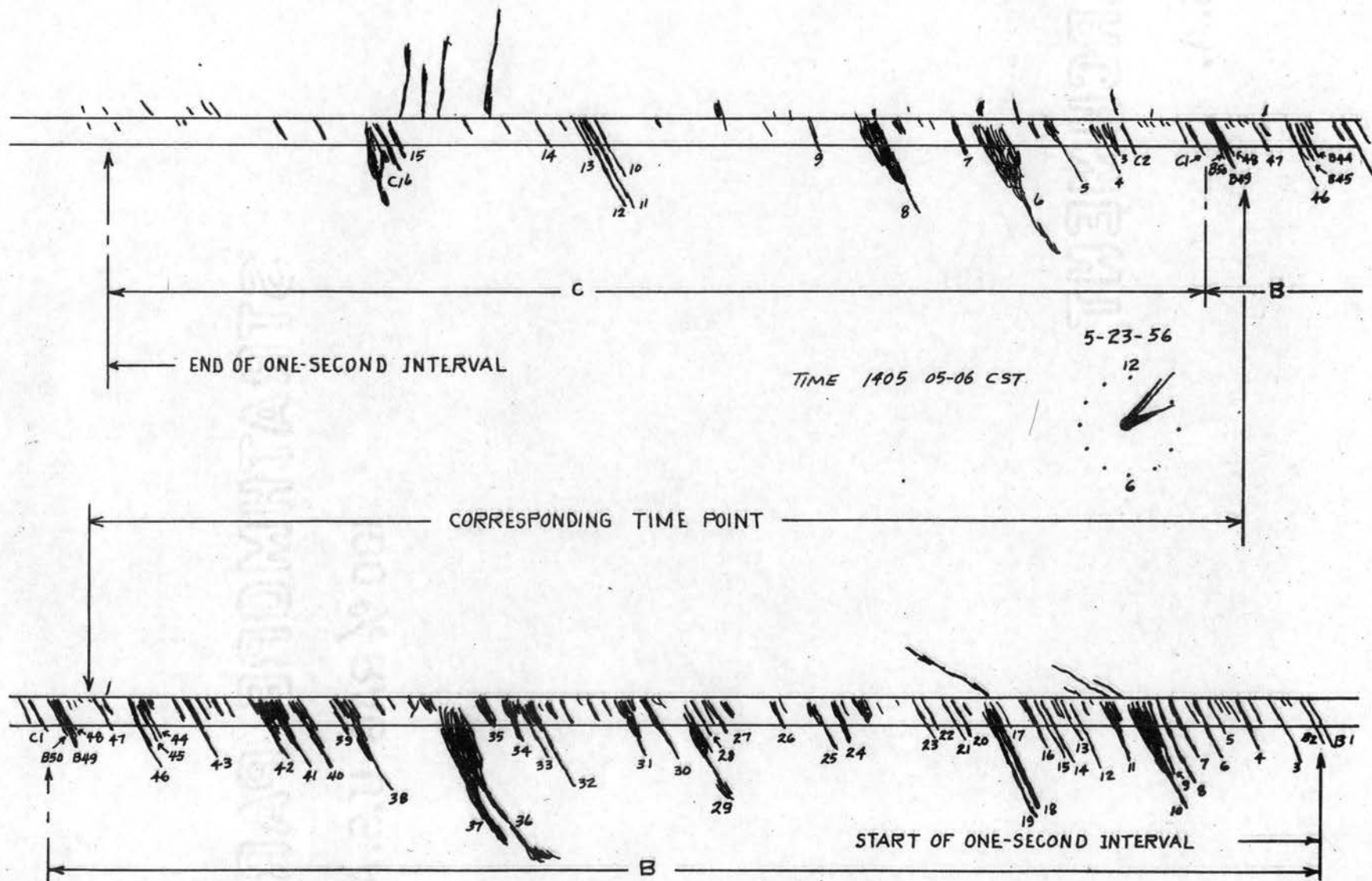


Figure 60. Sketch of the HFDF film record, 1405 05-06 CST, May 23, 1956.

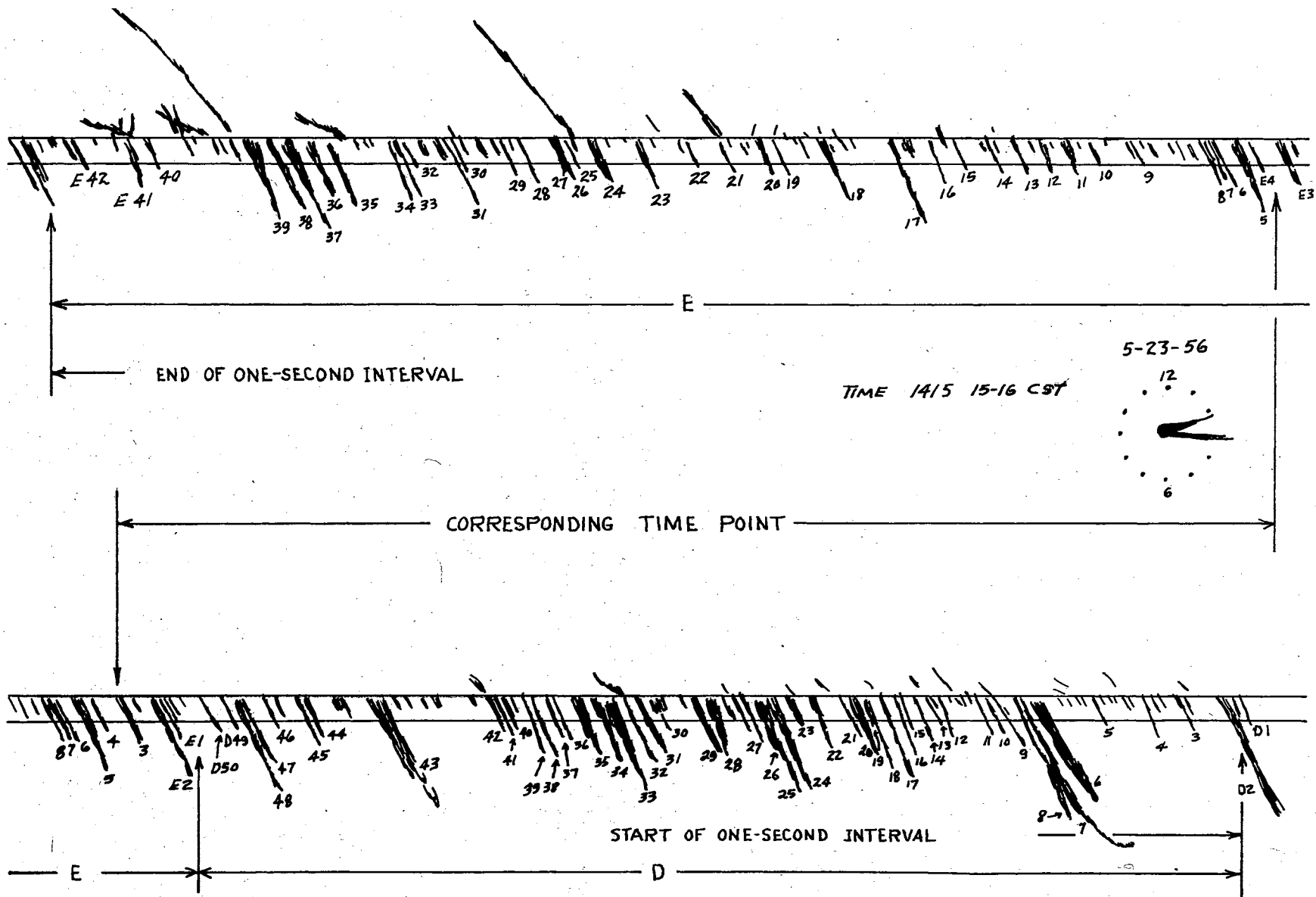


Figure 61. Sketch of the HFDF film record, 1415 15-16 CST, May 23, 1956.



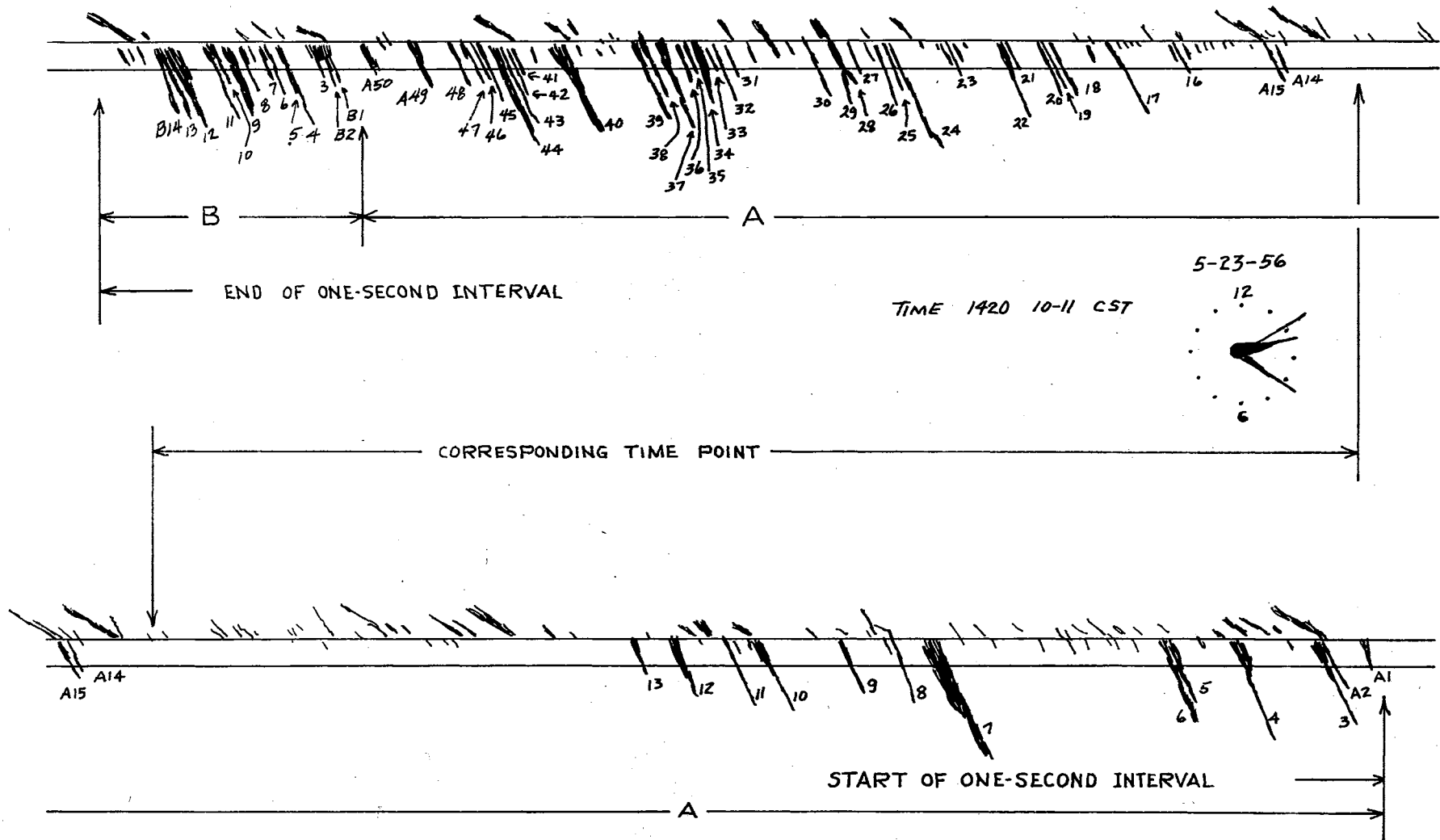


Figure 62. Sketch of the HFDF film record, 1420 10-11 CST, May 23, 1956.

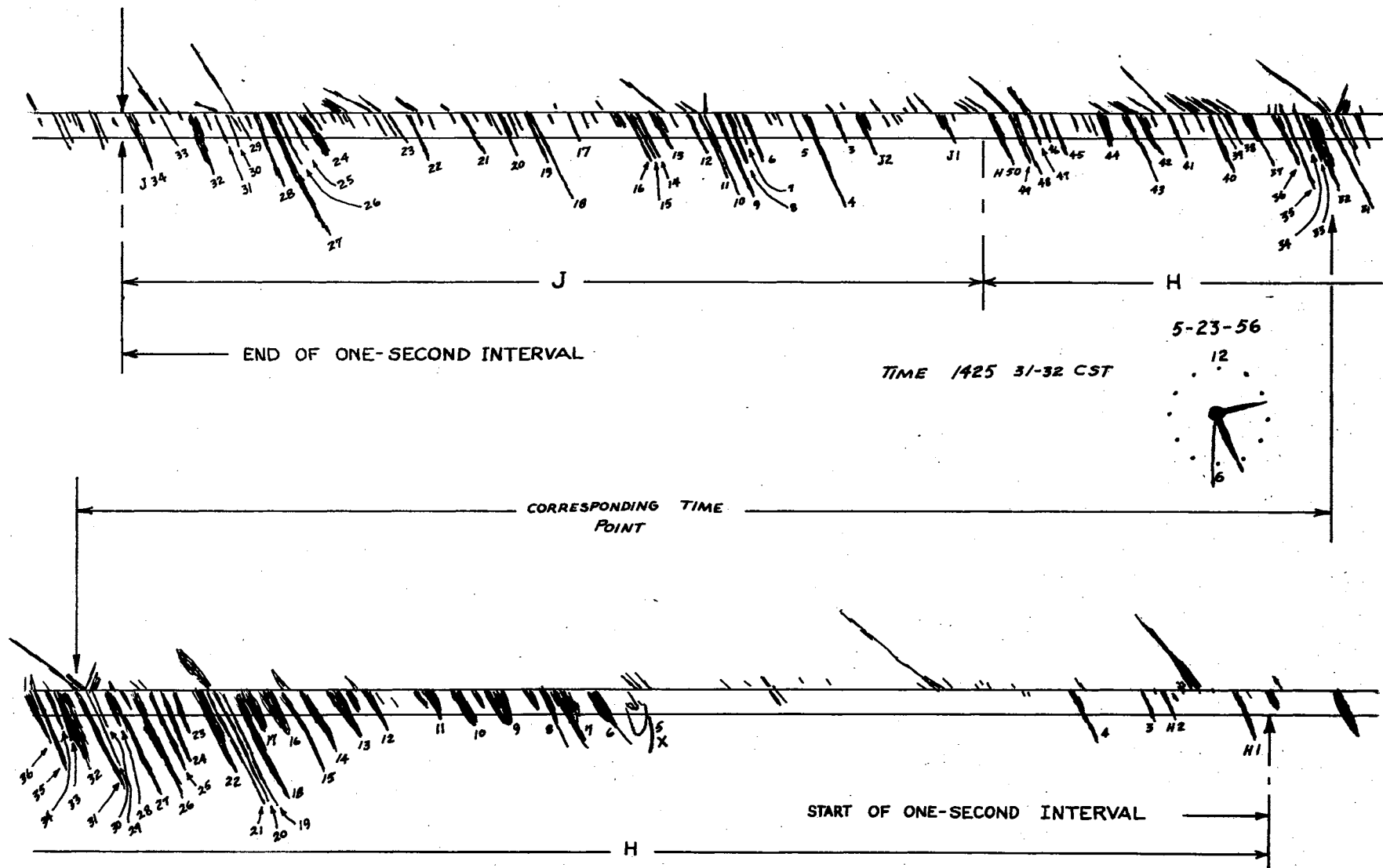


Figure 63. Sketch of the HFDF film record, 1425:31-32 CST, May 23, 1956.

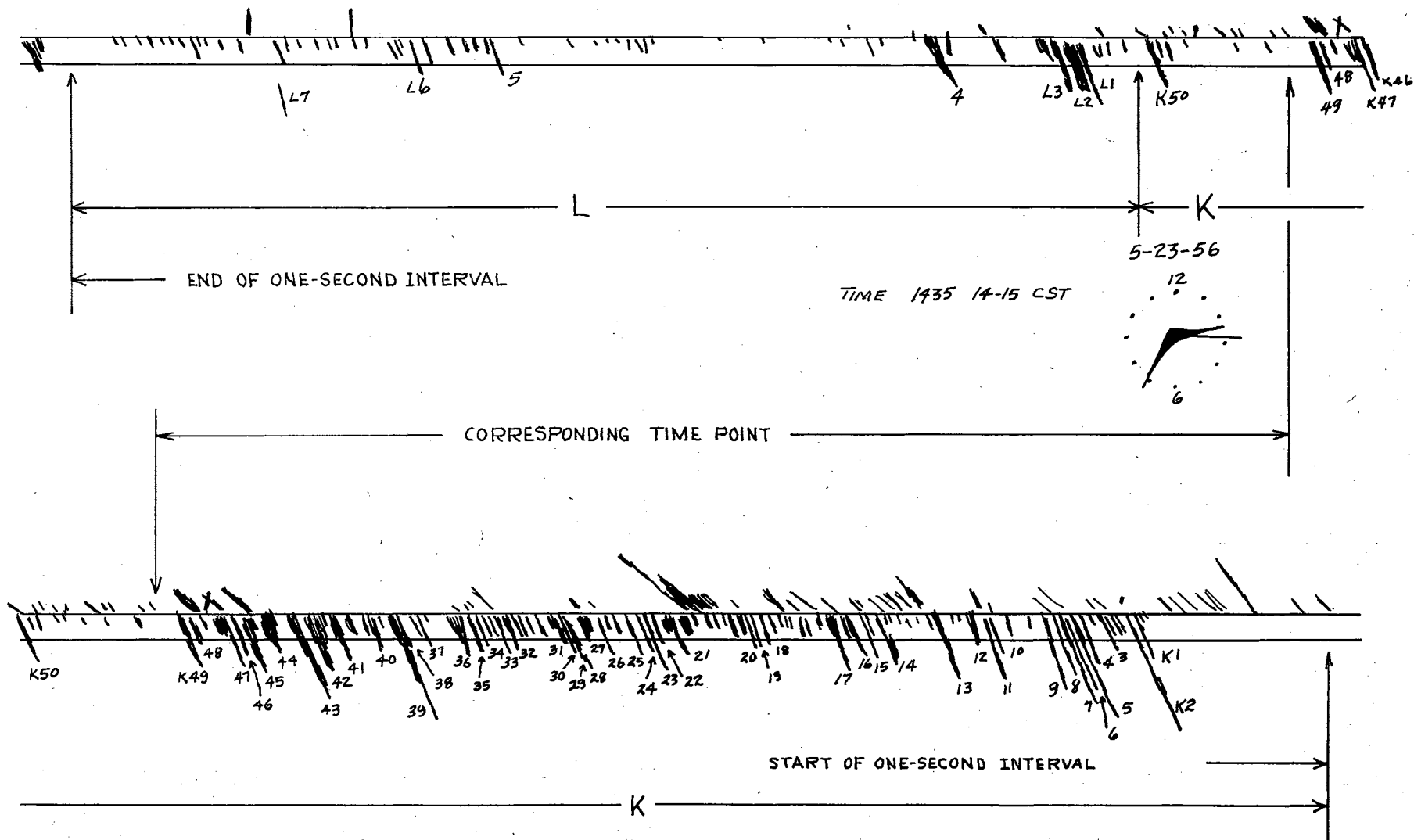


Figure 64. Sketch of the HFDF film record, 1435 14-15 CST, May 23, 1956.

TABLE I

SPHERIC ANGLES OF THE WATOVA TORNADO, MAY 23, 1956

1350-07-08 CST		1405-05-06 CST				1415-15-16 CST			
No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees
A1	63	B1	64.5	C1	63	D1	70.5	E1	61.5
2	62	2	63.5	2	68.5	2	65.5	2	62.5
3	59.5	3	62	3	68	3	63	3	63
4	58.5	4	64.5	4	65	4	69.5	4	62
A5	56	B5	63	C5	59.5	D5	67	E5	65.5
6	61	6	65	6	62.5	6	63	6	63.5
7	62	7	66	7	68	7	65	7	62.5
8	59	8	65.5	8	63	8	65	8	64
9	63	9	65	9	68.5	9	56	9	57
A10	61.5	B10	64.5	C10	62	D10	64	E10	65
11	60.5	11	67	11	62	11	68	11	65
12	52.5	12	64	12	62	12	72	12	66.5
13	59.5	13	64	13	63	13	67.5	13	65.5
14	61	14	61.5	14	64.5	14	70.5	14	67
A15	63	B15	62.5	C15	63	D15	69.5	E15	66
16	64	16	62.5	16	63.5	16	70.5	16	69
17	56	17	62	17		17	66.5	17	66.5
18	59	18	65.5	18		18	69	18	66.5
19	59	19	65.5	19		19	70.5	19	65.5
A20	66	B20	65.5	C20		D20	68	E20	68
21	71	21	62	21		21	62	21	66.5
22	69	22	62	22		22	68.5	22	67.5
23	63	23	63	23		23	68.5	23	68
24	59.5	24	67	24		24	67	24	66.5
A25	61.5	B25	60	C25		D25	65	E25	65
26	61.5	26	62	26		26	63	26	61
27	65	27	60.5	27		27	63	27	76
28	64.5	28	61	28		28	66	28	65.5
29	64	29	64	29		29	66	29	66.5
A30	66.5	B30	59	C30		D30	65	E30	63
31	64	31	60.5	31		31	60.5	31	63
32	68	32	61	32		32	64	32	65
33	66	33	59.5	33		33	66.5	33	65
34		34	62	34		34	66	34	68
A35		B35	61	C35		D35	68	E35	67
36		36	65	36		36	65	36	66.5
37		37	65	37		37	68	37	64.5
38		38	58	38		38	68	38	65
39		39	60.5	39		39	68	39	69
A40		B40	60	C40		D40	66.5	E40	70
41		41	60	41		41	65.5	41	69.5
42		42	61	42		42	64	42	62
43		43	62	43		43	64	43	
44		44	60.5	44		44	66.5	44	
A45		B45	62	C45		D45	64	E45	
46		46	61	46		46	64	46	
47		47	62.5	47		47	63.5	47	
48		48	63	48		48	64.5	48	
49		49	64	49		49	63.5	49	
A50		B50	65	C50		D50	64	E50	

TABLE II

## SPHERIC ANGLES OF THE WATOVA TORNADO, MAY 23, 1956

1420-10-11 CST				1425-31-32 CST				1435-14-15 CST			
No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees
F1	74	G1	70	H1	68.5	J1	68	K1	65	L1	66.5
2	62.5	2	70.5	2	70	2	68	2	63.5	2	66.5
3	64.5	3	70	3	70	3	68	3	66.5	3	67.5
4	69	4	66	4	64.5	4	66.5	4	69	4	64.5
F5	66.5	G5	66	H5	X	J5	68	K5	66.5	L5	73
6	66.5	6	68	6	54	6	71	6	67	6	73
7	64	7	69.5	7	69	7	71	7	68.5	7	70
8	70.5	8	68	8	67.5	8	69.5	8	70.5	8	
9	68	9	67	9	62	9	65.5	9	73.5	9	
F10	63.5	G10	67	H10	60	J10	67.5	K10	70	L10	
11	66.5	11	65	11	64	11	65.5	11	72.5	11	
12	66.5	12	65	12	66	12	66	12	76	12	
13	69.5	13	69.5	13	63.5	13	63	13	70	13	
14	66.5	14	73.5	14	61.5	14	64.5	14	69.5	14	
F15	65.5	G15		H15	63.5	J15	64.5	K15	68	L15	
16	67.5	16		16	65	16	65.5	16	65	16	
17	59.5	17		17	60.5	17	65.5	17	70.5	17	
18	61	18		18	64.5	18	60.5	18	68.5	18	
19	64.5	19		19	63	19	63	19	73	19	
F20	65.5	G20		H20	63	J20	65.5	K20	72	L20	
21	60	21		21	62	21	61	21	68	21	
22	66.5	22		22	65.5	22	66.5	22	70	22	
23	69	23		23	68	23	56	23	71	23	
24	64	24		24	68	24	63	24	67	24	
F25	71.5	G25		H25	65.5	J25	63.5	K25	68.5	L25	
26	70.5	26		26	65.5	26	63.5	26	67	26	
27	67	27		27	64	27	63	27	70	27	
28	62	28		28	66	28	69	28	67.5	28	
29	72	29		29	66	29	61	29	68.5	29	
F30	65	G30		H30	66	J30	66	K30	68	L30	
31	66	31		31	62.5	31	65.5	31	69	31	
32	67	32		32	67.5	32	69	32	70	32	
33	66.5	33		33	66.5	33	64.5	33	71	33	
34	72.5	34		34	65.5	34	66.5	34	72.5	34	
F35	68	G35		H35	67.5	J35		K35	72.5	L35	
36	68	36		36	65.5	36		36	70.5	36	
37	65.5	37		37	62	37		37	67.5	37	
38	65.5	38		38	62	38		38	68.5	38	
39	66	39		39	60.5	39		39	66.5	39	
F40	62.5	G40		H40	67	J40		K40	69.5	L40	
41	69.5	41		41	66.5	41		41	68	41	
42	67	42		42	60	42		42	69.5	42	
43	65	43		43	64	43		43	66	43	
44	64.5	44		44	67.5	44		44	70	44	
F45	70	G45		H45	69	J45		K45	70.5	L45	
46	67.5	46		46	68.5	46		46	68.5	46	
47	67.5	47		47	65	47		47	70	47	
48	62	48		48	67	48		48	70	48	
49	65	49		49	67	49		49	68.5	49	
F50	68	G50		H50	66	J50		K50	68	L50	

plotted on an azimuth scale. Since all of the directional pips appearing in each sketch occur in a one-second interval, a scheme was devised to obtain a plot similar to that which would result from a scanner type counter. The assumed scanner has a 2-degree effective slit width and rotates at a one-degree per second rate.

If such a group of directional pips as those under consideration in a particular sketch were repeating at a one cycle per second rate, the resulting plot would present a count at each one-degree abscissa that would correspond to all of the pips that were in the two-degree interval spanning that abscissa point. To obtain such a plot, one needs merely to tabulate the total number of directional pips that occur at each azimuth value during the one-second interval under consideration. From this tabulation, represented graphically in Figures 65 through 70 by the small dots near the azimuth axis, a count ordinate for each degree of azimuth that corresponds to the total number of directional pips within  $\pm 1^\circ$  of this point is obtained. The resulting plots resemble closely the envelope of the actual HFDF counter records that were obtained during the storm. When these plots are compared to the HFDF counter records, a close agreement is revealed.

The film count for 1355 CST (Figure 65) shows a maximum count of 11 pips per second at  $62^\circ$ . The HFDF counter record for the 1354 CST scan (Figure 40) shows a maximum count of 10 pips per second at  $58^\circ$  and of 9.6 pips per second at  $65^\circ$ . The maximum count at  $58^\circ$  represents the fact that a strong spheric burst at the active angle occurred when the scanning slit was at  $58^\circ$ , and because of the effective slit width there was sufficient light transmitted from the cathode-ray tube through the slit to the photo-electric counter tube to cause this count. The

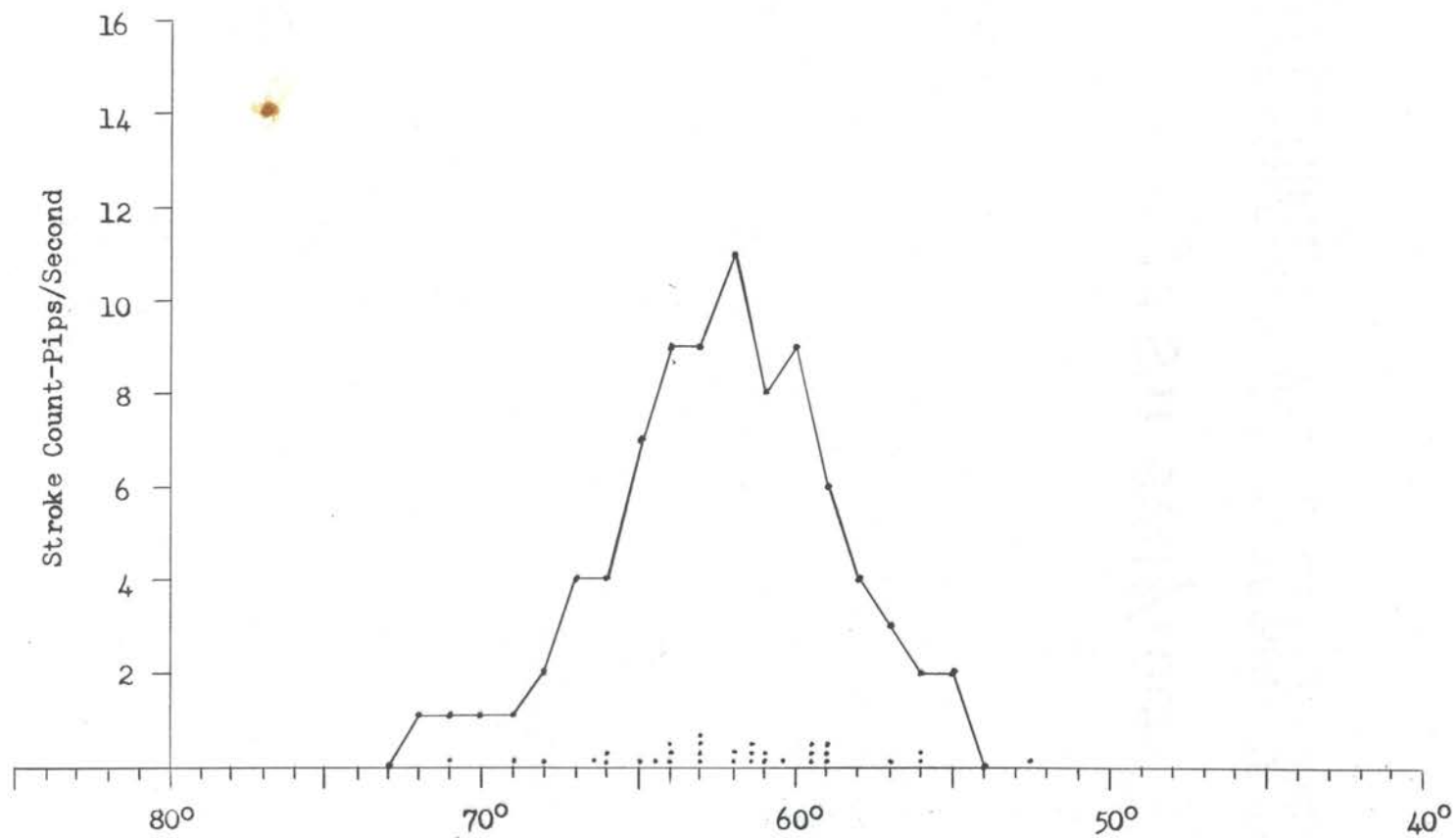


Figure 65. Plot of film count for Watova Tornado, 1355 07-08 CST, 5/23/56.

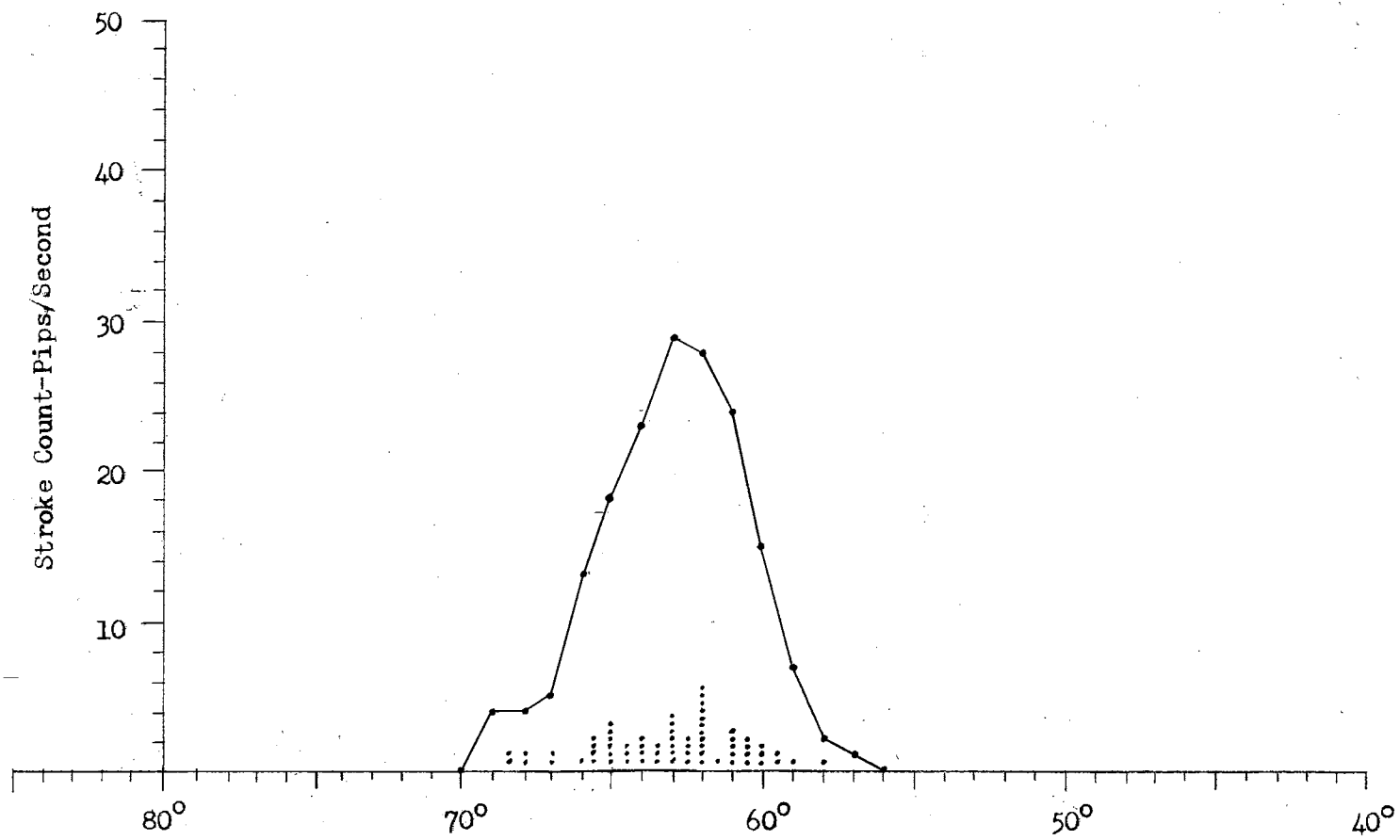


Figure 66. Plot of film count for Watova Tornado, 1405 05-06 CST, 5/23/56.



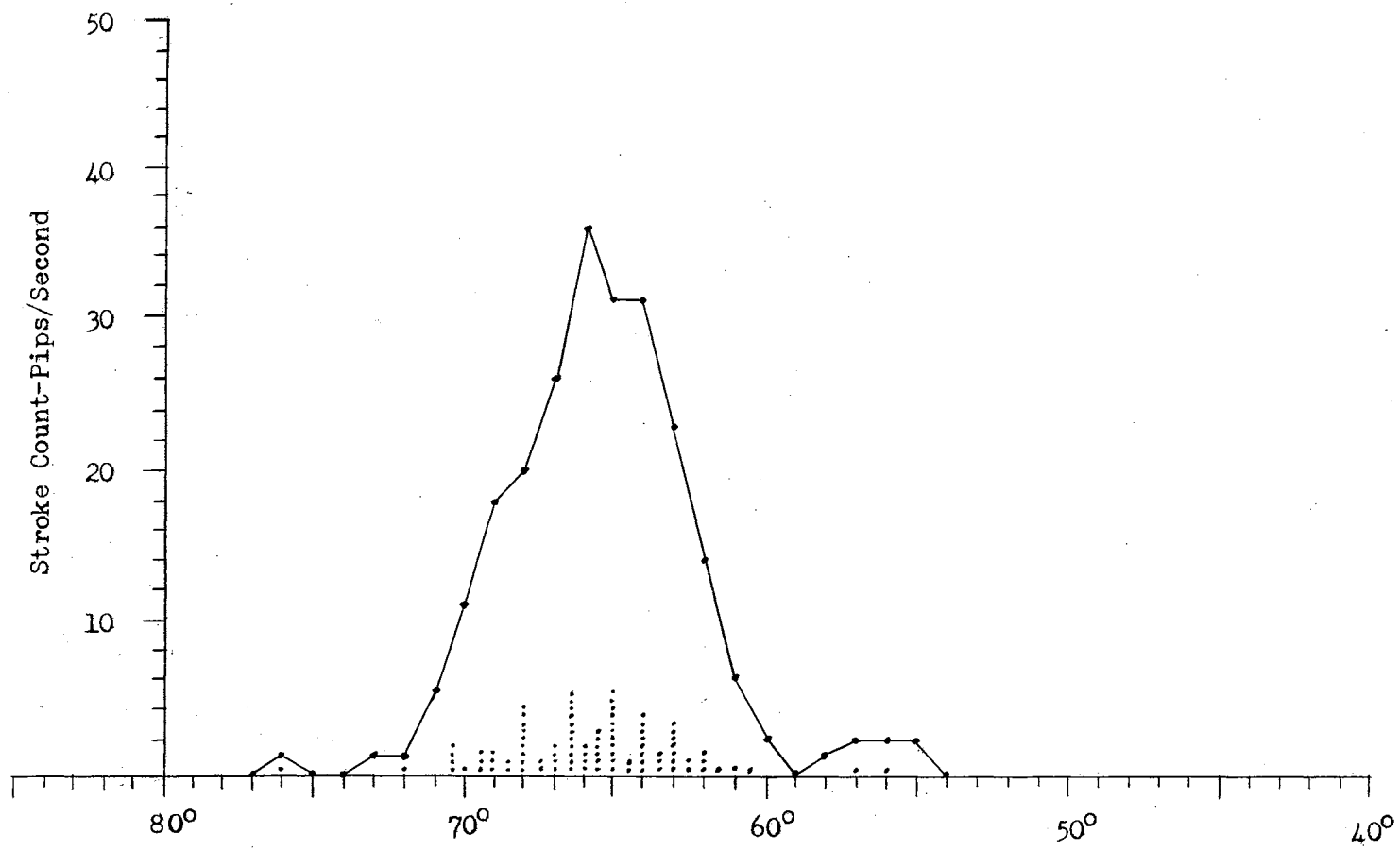


Figure 67. Plot of film count for Watova Tornado, 1415 15-16 CST, 5/23/56.

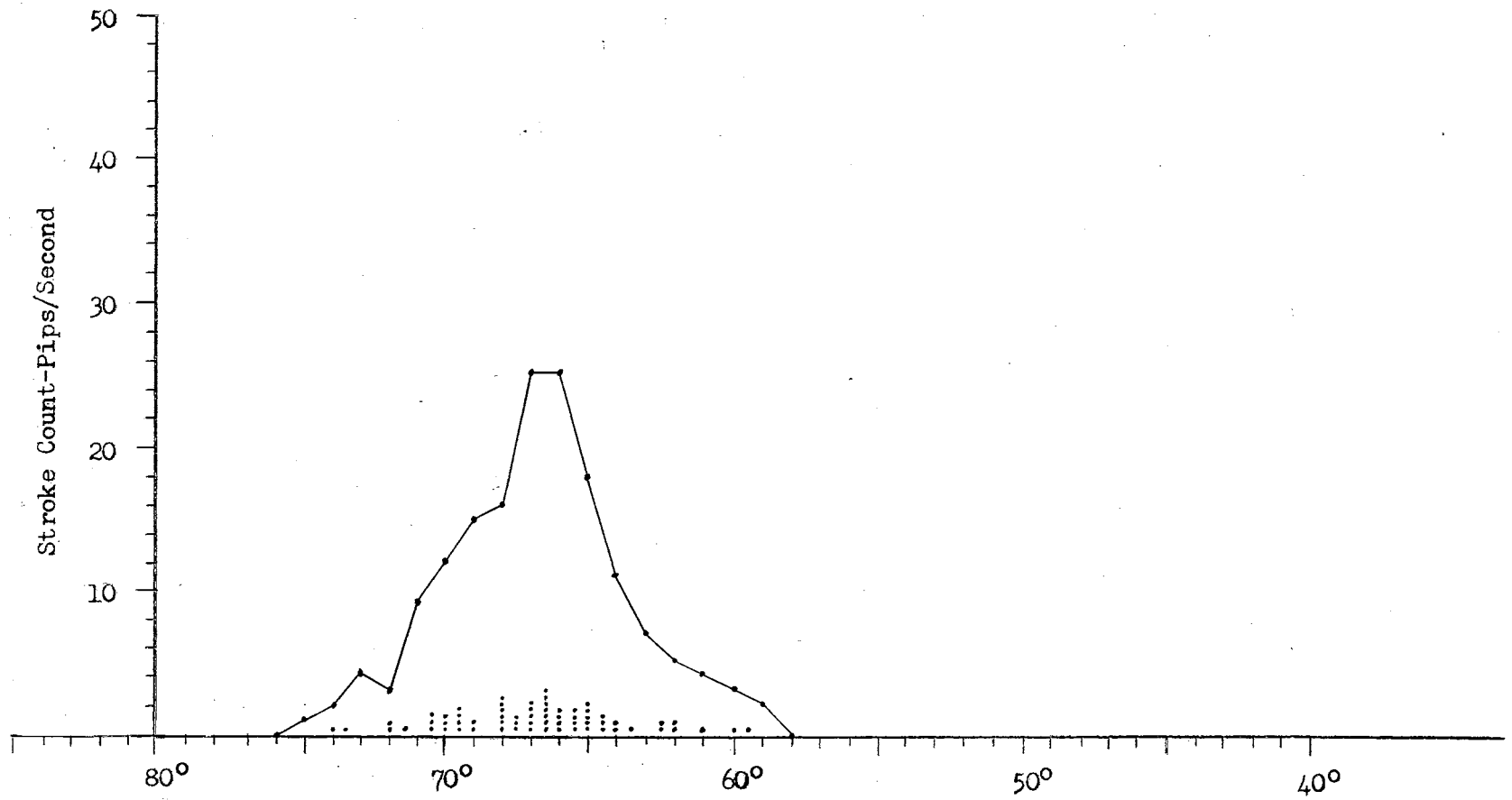


Figure 68. Plot of film count for Watova Tornado, 1420 10-11 CST, 5/23/56.

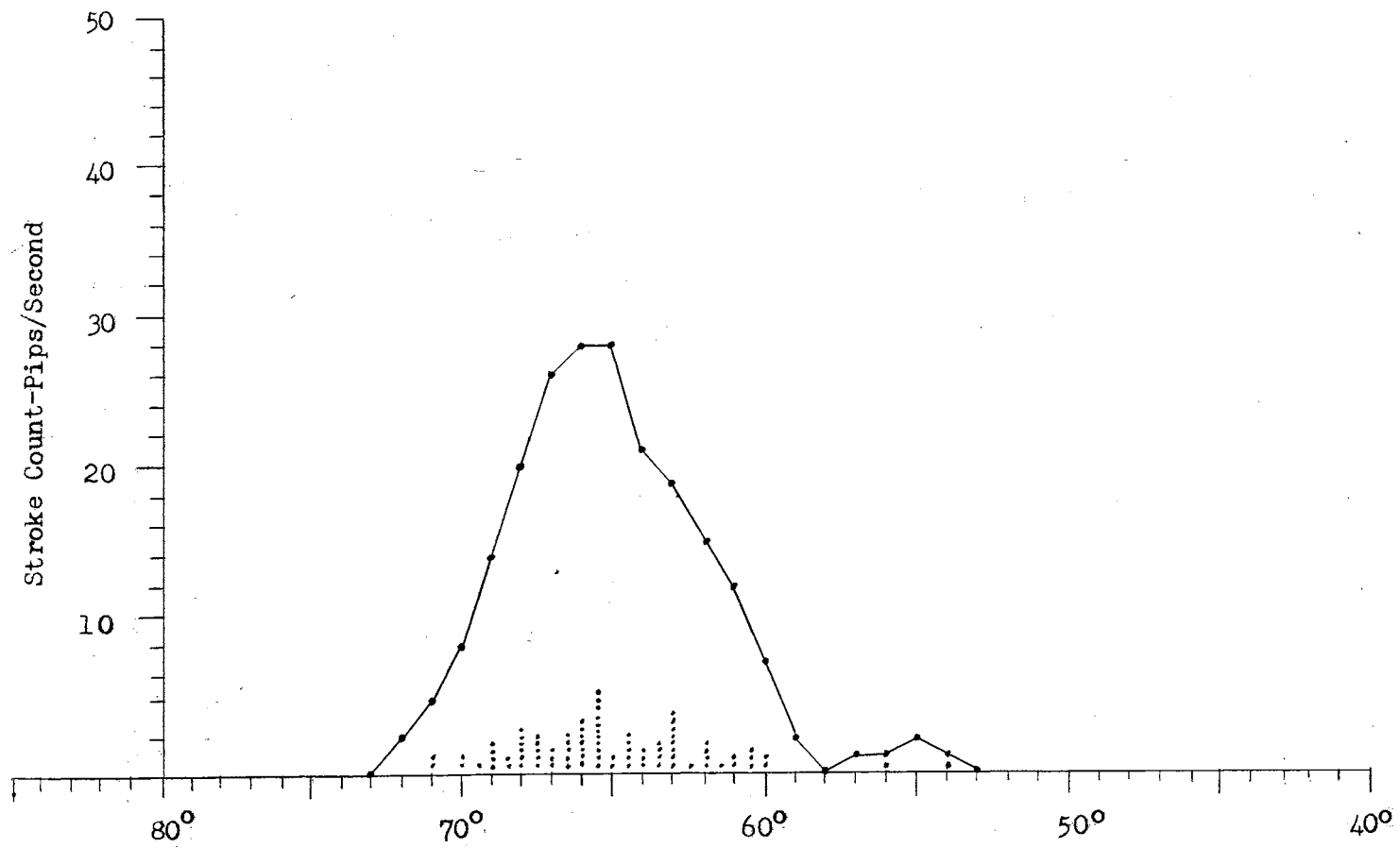


Figure 69. Plot of film count for Watova Tornado, 1425 31-32 CST, 5/23/56.

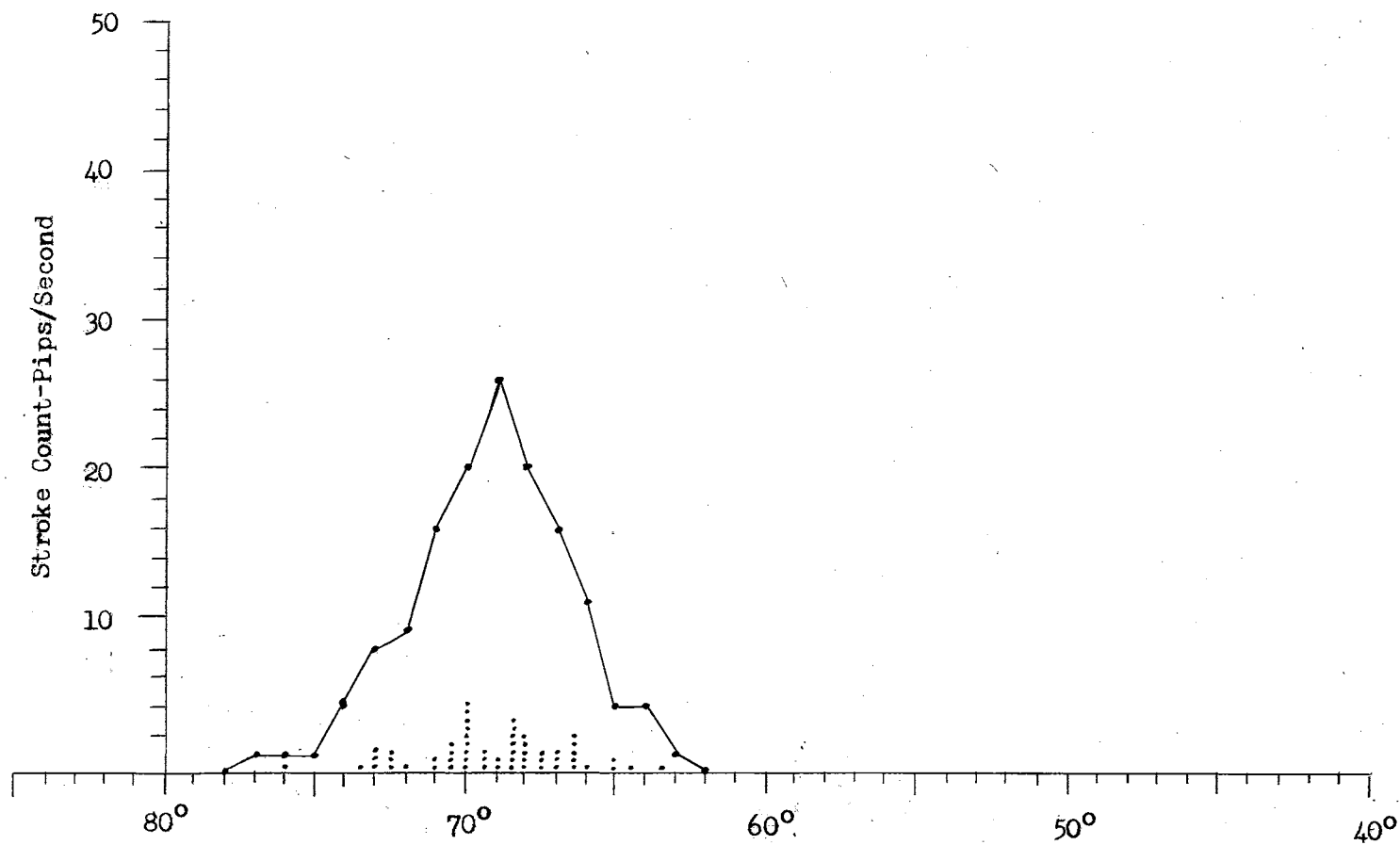


Figure 70. Plot of film count for Watova Tornado, 1435 14-15 CST, 5/23/56.

mean azimuth for the  $65^{\circ}$  and the  $58^{\circ}$  readings is  $61.5^{\circ}$ , an azimuth very close to the film count angle.

The second film count for 1405 CST (Figure 66) has a maximum count of 29 pips per second at an azimuth of  $63^{\circ}$ . The HFDF counter record for the 1406 CST scan (Figure 41) shows a maximum count of 26 pips per second at an azimuth of  $62^{\circ}$ .

The film count for 1415 CST (Figure 67) has a maximum count of 36 pips per second at an azimuth of  $66^{\circ}$ . The HFDF counter record for the 1412 CST scan (Figure 42) has a maximum count of 36 pips per second at  $65^{\circ}$ .

The film count for 1420 CST (Figure 68) has a maximum count of 25 pips per second at  $66^{\circ}$  and  $67^{\circ}$ , which corresponds to the HFDF counter record for the 1418 CST scan (Figure 43) that has a maximum of 24 pips per second at  $65^{\circ}$ .

The 1425 CST film count (Figure 69) has a maximum at  $65^{\circ}$  -  $66^{\circ}$  of 28 pips per second. The corresponding HFDF counter record for the 1424 CST scan (Figure 44) has a maximum count of 31 pips per second at  $66^{\circ}$ .

The 1435 CST film count (Figure 70) has a maximum of 26 pips per second at an azimuth of  $69^{\circ}$ . The corresponding HFDF counter record for the 1436 CST scan (Figure 45) has a maximum count at  $65^{\circ}$  of 19 pips per second.

The preceding comparison of film counts with HFDF counter records illustrates that there is a close agreement between the counts resulting from the two methods. The HFDF counter record is made continuously and automatically once every six minutes and is immediately available for determining the severity of a storm during the actual time that the storm

is in existence. The film record, on the other hand, must be developed and then analyzed by a time consuming method.

An analyst can make preliminary studies which require only about 30 minutes for each second of film, but a thorough analysis requires approximately two hours for each second of film. Naturally, it takes many weeks to completely analyze a single storm. In the course of the 1956 tornado season some 20,000 feet of 35 mm film were used. Out of this tremendous amount of accumulated data many interesting studies will evolve. At this time only a small percentage of the most important films have been investigated. The HFDF counter is not a complete solution to the problem of rapidly determining the intensity of a storm, but it certainly is a step in the right direction.

A composite picture is shown in Figure 58 to illustrate how the various active angles appear for such a storm. Many storms are so intense that only the one-second or two-second time exposures are of any value. The longer time exposures are very overexposed because of the intense activity of the more intense storm centers.

The waveform recording equipment was not in operation during the Watova storm. Mr. Arthur Bishop, a graduate Electrical Engineering student, is investigating the value of the waveform in relation to the direction finding equipment. The results of these investigations will appear in Mr. Bishop's thesis.

The optical stroke recorder was not in operation for this storm which occurred during the day light hours. Mr. E. Alan Roemer, another graduate Electrical Engineering student, is investigating the relationship between the AN/GRD-1A, high frequency direction finder and the photograph of the actual lightning discharge. The result of these

investigations will appear in Mr. Roemer's thesis.

Film Count - HFDF Counter Correlation on the Bryan, Texas Tornado,

April 5, 1956

A comparison between the film record and the HFDF counter tape for the Bryan, Texas, tornado reveals that a much closer correlation could have been obtained had the HFDF counter been able to respond to all of the very small amplitude pips which arrived from the distant storm. Actually the counter exhibited the correct angle for the tornado, but its count was too low because of the tremendous distance to the tornado area.

An evaluation of the film data shows that the stroke count would have been recorded as tornadic in nature by the HFDF counter had the storm been closer to the Oklahoma A. and M. College Tornado Laboratory. The time of the Bryan tornado has been fixed as 1515 CST on April 5, 1956, and the film record for a one-second interval at this exact time is reproduced in Figure 71. Because details were lost in the printing process, the film reproduction is insufficient to illustrate the intense activity at the Bryan, Texas, azimuth of  $173^{\circ}$ . To clearly demonstrate the activity at this azimuth, a tracing of the same one-second interval was made from the film viewer presentation and is shown in Figure 72. The entire photographic run was sketched and the angle of each readable pip was tabulated. The tabulated result is shown in Table III. Each directional pip was numbered so that the record could be easily checked.

The data from Table III is shown plotted as a function of azimuth in Figures 73 and 74. The plot shown in Figure 73 is for the one-second

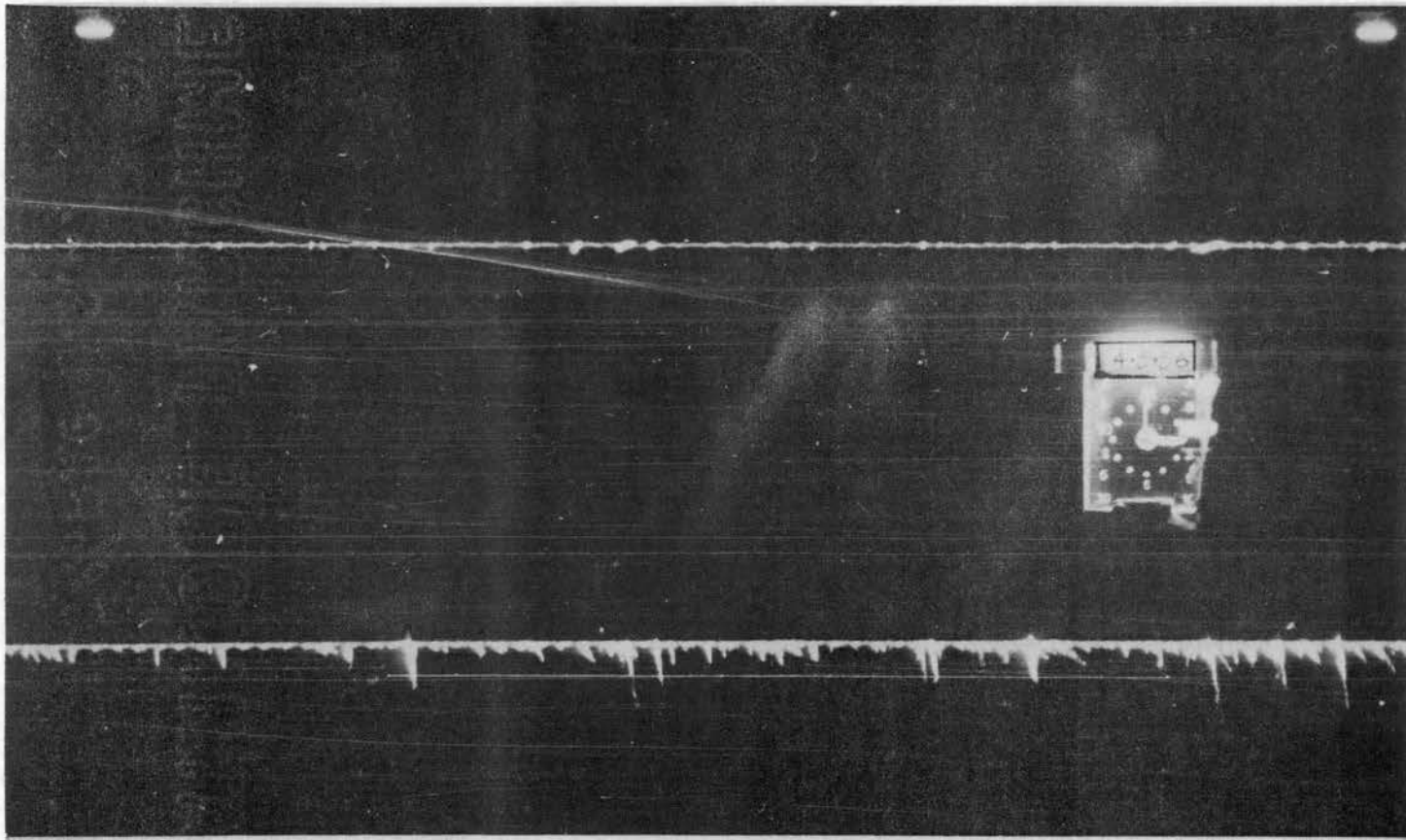


Figure 71. Sferic record of Bryan, Texas, tornado, 1515 CST, April 5, 1956.



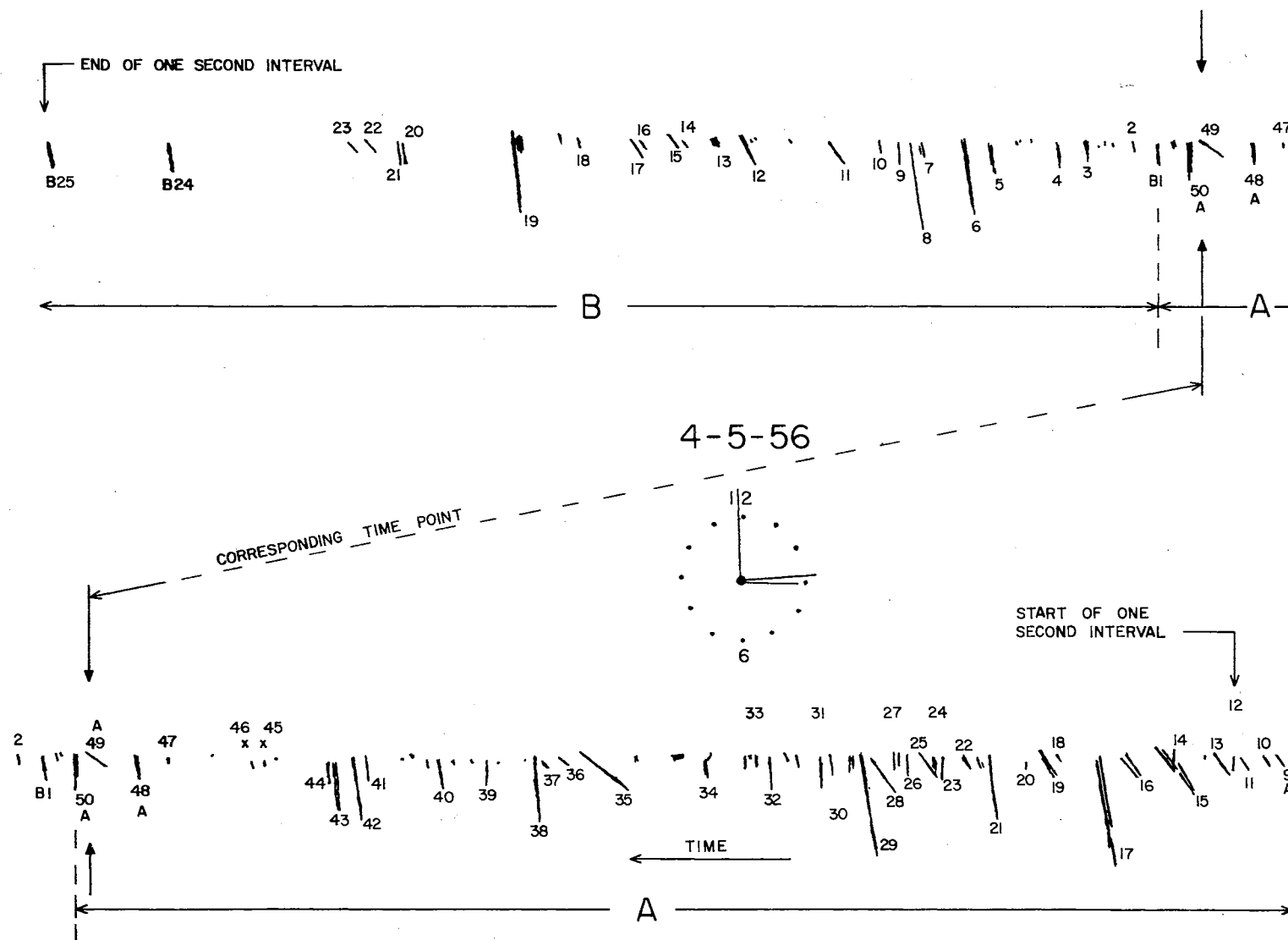


Figure 72. Enlarged sketch of the one-second interval shown in Figure 71, showing detail of count.

TABLE III

SFERIC ANGLES OF THE BRYAN TORNADO, APRIL 5, 1956

1515-00 Through 1515-03							
No.	Degrees	No.	Degrees	No.	Degrees	No.	Degrees
A1	175	B1	173	C1	148	D1	157.5
2	145.5	2	174	2	148	2	173
3	176	3	175.5	3	142.5	3	174.5
4	146	4	172	4	146	4	172
A5	148	B5	173.5	C5	139	D5	X174
6	147	6	173	6	X139	6	
7	144	7	172.5	7	144	7	141
8	144	8	172.5	8	177	8	X175
9	146	9	172.5	9	144	9	X175
A10	146	B10	173	C10	144	D10	146
11	146	11	143	11	147.5	11	176
12	176.5	12	147.5	12	175.5	12	176
13	145.5	13	150	13	143.5	13	176
14	176	14	150	14	151.5	14	176
A15	144	B15	150	C15	170	D15	X174
16	145	16	150	16	176	16	X170
17	172.5	17	150	17	143	17	158
18	X150	18	173	18	144	18	X172.5
19	148	19	173.5	19	175.5	19	159
A20	171	B20	173.5	C20	149.5	D20	X
21	171	21	173.5	21	149.5	21	146
22	150	22	135.5	22	X	22	X146
23	174.5	23	135.5	23	174.5	23	X149
24	174.5	24	174	24	175.5	24	X170
A25	147	B25	177	C25	175.5	D25	176
26	172	26	177	26	X	26	176
27	X	27	152.5	27	174	27	X176
28	145	28	139	28	143	28	X176
29	171	29	147	29	X	29	X176
A30	170	B30	X173	C30	X139	D30	176
31	173	31	136.5	31	163.5	31	X176
32	174	32	136.5	32	146	32	X176
33	166	33	139.5	33	146.5	33	156
34	170	34	X139.5	34	177	34	158
A35	124.5	B35	147	C35	177	D35	156
36	124.5	36	X143.5	36	X166	36	156
37	124.5	37	142	37	X178	37	170
38	176	38	X143.5	38	147	38	172
39	176.5	39	X	39	147	39	172
A40	172	B40	X	C40	176	D40	174.5
41	172.5	41	143.5	41	X155	41	174
42	172	42	143.5	42	X155.5	42	
43	173	43	143.5	43	142.5	43	
44	173	44	143.5	44	X146	44	
A45	X174	B45	145	C45	X175.5	D45	
46	X174	46	X	46	X	46	
47	X174	47	149	47	161	47	
48	174.5	48	146.5	48	159.5	48	
49	133.5	49	X178	49	X160	49	
A50	173	B50	178	C50	142	D50	

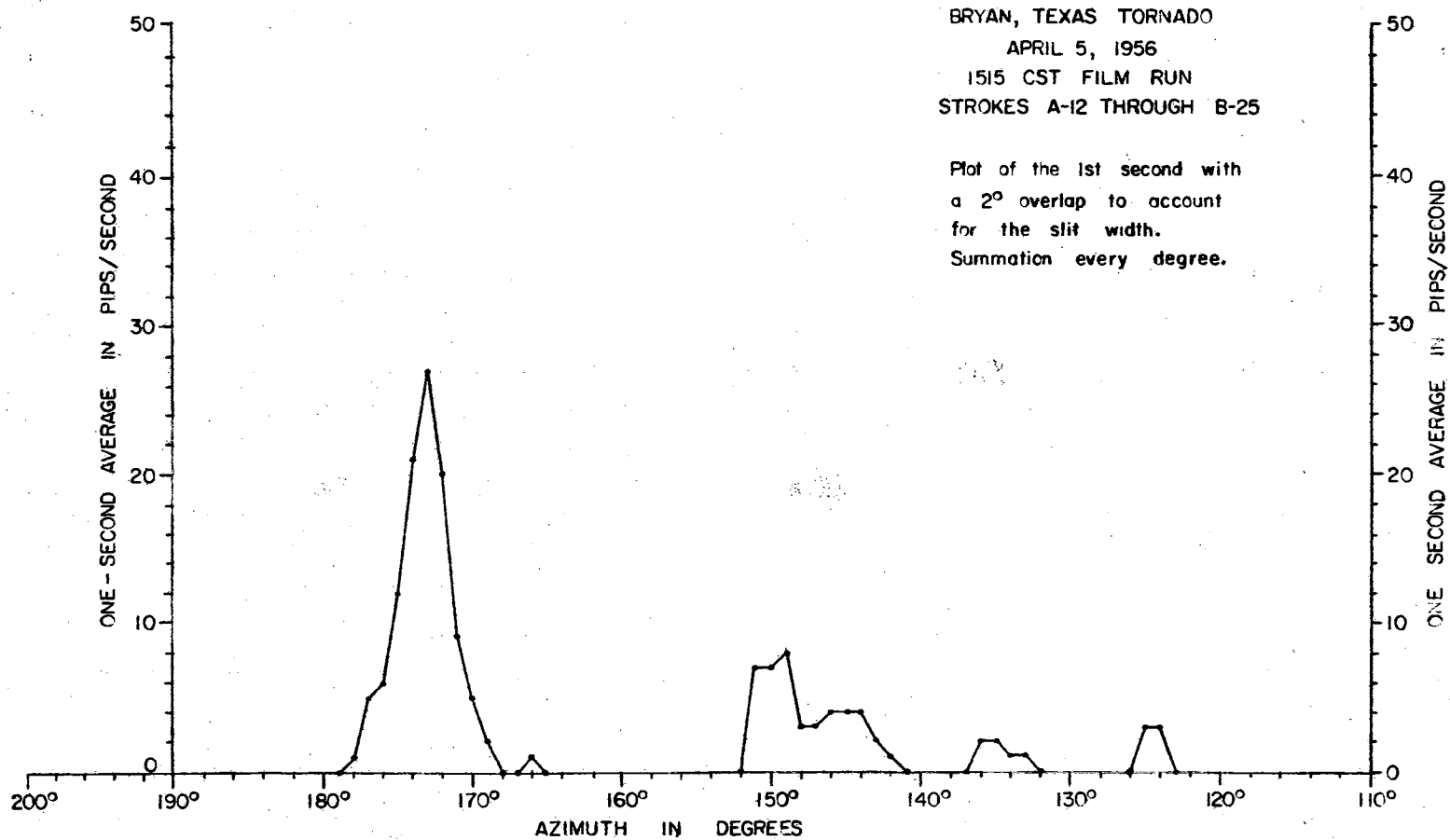


Figure 73. Plot of film count for 1st second of Bryan Tornado.

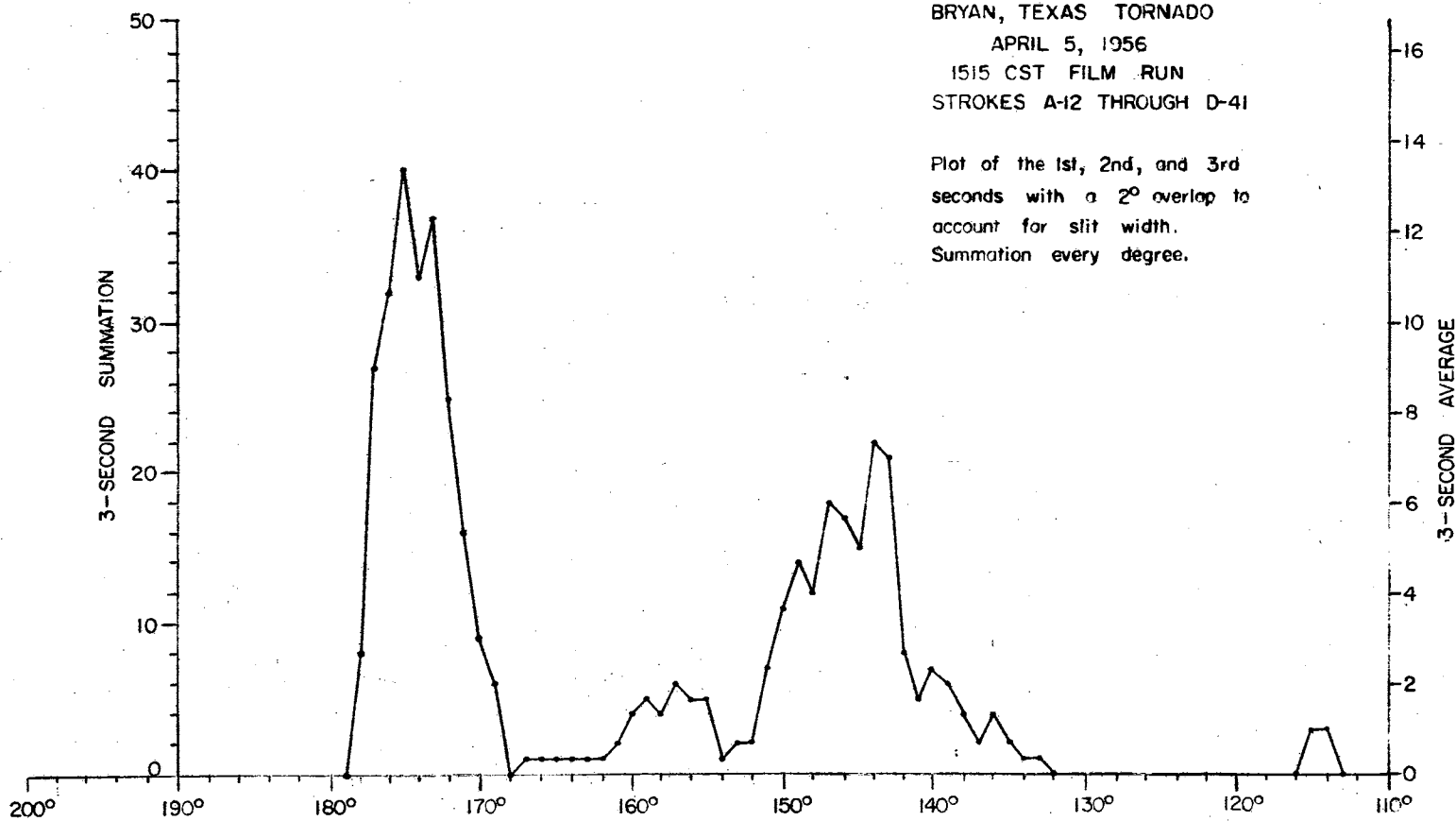


Figure 74. Plot of film count for first three seconds of Bryan Tornado.

interval illustrated in Figure 71 and Figure 72. The ordinate at each degree represents the sum of all pips that occurred within a  $\pm$  one-degree interval for the period under study. In Figure 74 the sum of all strokes over a three-second interval, including the one-second interval of Figure 73, is plotted and two ordinate scales are shown that, for the 3-second interval, give the sum and the average count, respectively. The ordinate at each degree was chosen to represent all of the pips within  $\pm$  one-degree of this ordinate to more closely represent the counter recording which exhibits an effective slit width of several degrees.

The maximum count shown in Figure 73 occurs at an azimuth of  $173^{\circ}$ ; the maximum for the 3-second interval shown in Figure 74 results in a maximum at both  $173^{\circ}$  and  $175^{\circ}$ , an average of  $174^{\circ}$ . The angle of Bryan, Texas, with respect to the Oklahoma A. and M. Tornado Laboratory is  $173.5^{\circ}$  as read on a large aeronautical map of this section of the United States.

Bryan, Texas, would be considered as in the secondary range of the tornado equipment. It is almost too distant to provide sufficient signal to initiate the HFDF counter on severe storm conditions. In the case of severe storms that are within the primary range of the tracking equipment, like the Watova tornado, there has been close correlation between the equipment indications and storm observer reports.

A one station HFDF system must rely on radar to establish the storm position. A problem is sometimes encountered in which the radar displays several echoes at the same azimuth and there is no way of ascertaining which echo is the active one. The Air Weather Service has requested HFDF units at their points of operation and expect to have them available late in the 1957 tornado season. When similar HFDF sets are used, a triangulation

method of storm location should prove accurate in a large percentage of the cases.

It has been shown in numerous cases that the radar alone cannot successfully track severe storm centers. A peculiar hook-like display is sometimes experienced on the radar for severe tornadoes, but these are seldom noticed on smaller tornadoes. The 3-cm radar displays a squall line in motion across the state, but this display gives no indication of the movement of the severe storm centers inside the squall line. Successive plots of the severe storm centers, obtained by the intersection of the most severe HFDF azimuth indications with the radar display, indicate that a severe storm can move in an angular direction different from the apparent motion of the squall line. For this reason, the prediction of the path of a storm by radar observations alone may frequently be in error. When a triangulation system employing HFDF equipment in conjunction with instantaneous evaluation units is installed, the area served by this system can be alerted in time for people to seek shelter. If but one life is saved, the research will have been worthwhile.

## CHAPTER VIII

### SUMMARY AND CONCLUSIONS

There are many problems encountered in research. One must set his overall objective and not deviate too far from it as he proceeds. Sometimes this is difficult, because many interesting problems arise. Since the objective must be reached, these problems must be merely noted and left for the researchers to come. The tornado project was no exception. Many problems are only partially solved; some are solved in an acceptable manner, but their solution could be greatly improved; and a large number are yet untouched. This chapter serves to point out a few cases where improvement could be brought about, and other cases which should be thoroughly investigated.

Although the original contract for the tornado project was awarded on the merits of a waveform detection system, little further technology that can definitely connect the high frequency waveform to the tornado activity has been obtained from this system. This fact has, however, been proved in an indirect method. The HFDF filters the 150 kilocycle component from the complex spheric waveform, and exhibits much greater activity when the storm is tornadic than it does normally. The problem encountered in correlating the spheric waveform with the spheric arrival angle evolves from the displacement of the waveform by the low frequency components of the complex wave. A multitude of spherics arrive every second and only a limited number of them can be displayed by the waveform cathode-ray tube. It is impossible to definitely associate each

waveform with its corresponding direction finder display. An easy solution has been successfully tried by merely eliminating all direction finder display except the ones corresponding to the waveforms. This method was not satisfactory and a second method was attempted. The second method uses a filter that eliminates all frequency components whose period is greater than the time base employed in the waveform sweep generator. This method allows for easy direction-waveform association, but changes the appearances of the waveform so drastically that it was abandoned.

The waveform analyzer has been modernized by changing from a single-frame relay-type photographic recording system to an all electronic system. The rate of waveform presentation has been increased from less than 10 per second to as many as 68 per second.

The three most important items used in the present tornado tracking system are the HFDF, the HFDF counter, and radar. With these three devices it is possible to detect and track 90% of the severe storms occurring within a 120-nautical-mile radius of the laboratory. Even with this high percentage of success, there are some phases of the system that should receive further study.

It is known that on some storm systems, especially in the summer and fall months, that a tremendous burst of electromagnetic energy is detected. These bursts appear as almost continuous activity on the HFDF record and tend to give tornadic counter records without culminating into a tornado. It is possible that an HFDF receiver that operates on some frequency different from 150 KC should be used. With such an assumption, design was begun during the 1956 tornado season on a multiple-frequency direction finder. This direction finder is being designed to switch



automatically to a number of pre-selected operating frequencies within the range of 20 KC to 500 KC. The data obtained from the unit will be used to determine if an optimum operating frequency exists and to investigate the theory that the energy distribution in the electromagnetic spectrum shifts from the low to the high frequency region as the storm approaches the tornadic stage. The Air Force Cambridge Laboratory is investigating the design of such a multi-frequency receiver in connection with the AWS sferic network.

Despite the improvements that could be enacted, the laboratory continues to present the best record of any tracking group in the nation. After the 1956 tornado season, the Air Weather Service requested a system of direction finders similar to the HFDF unit developed at the tornado laboratory.

Within the primary range of the tornado laboratory, the method of tracking consists of the interpretation of data from successive radar, visual HFDF, and HFDF counter records. The operator makes a radar plot on a map of Oklahoma area every fifteen minutes. A visual reading of the HFDF presentation provides an accurate determination of the most active sferic angular direction. The HFDF counter record provides an index to the severity of these active sferic angles. The portion of the radar plot which corresponds to these most active angles is carefully noted on the Oklahoma map, because each of these represents a severe storm center. The next 15 minute plot reveals the direction of travel for these severe storm centers.

Whenever the HFDF counter indicates that a particular storm center is approaching the critical count of 20 pips per second, it is carefully watched. The direct telephone line to the AWS in Kansas City is

continually busy with the exchange in data between the tornado laboratory and the AWS network. If the count for the severe storm surpasses 20 pips per second, the Weather Bureau in Kansas City is notified by AWS. Before a tornado alert is issued on the sferics count, several of the AWS stations must be reading high activity, similar to that from the tornado laboratory.

In the meantime, the Stillwater Police Department is notified of the serious nature of the condition, and they in turn notify the Oklahoma Highway Patrol to be on the lookout for a tornado funnel. By close cooperation between the tornado laboratory and the police units, a great deal of benefit is derived by many people. The laboratory receives valuable information concerning the accuracy of its observations, and the general public obtains an alerted observer group that warns them whenever a tornado is sighted.

#### Suggestions for Future Improvements

In the course of observations, the operator must use the HFDF presentation for accurately determining the most active sferic angles. This often takes considerable time because of the erratic nature of a storm. A new tube that can alleviate this difficulty has been developed by the Hughes Research and Development Laboratories, and called the Memotron<sup>1</sup>. The Memotron is a direct-display, cathode-ray storage tube that retains traces and transients until intentionally erased.

The Hughes Company uses this tube in the Memo-Scope<sup>2</sup>, which could

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<sup>1</sup>Proceedings of the IRE, 1956-1957 Directory, p. 117.

<sup>2</sup>Proceedings of the IRE, February, 1957, p. 9A.

be employed for the visual HFDF scope. When fitted with an azimuth hair-line, the HFDF display could be triggered on the Memo-Scope for a short period. Then the operator could read the active angles quickly and easily. Once the reading was tabulated, the display could be electrically erased. As an added feature, the display could be triggered on the screen at regular intervals.

The Memo-Scope, which has d.c. amplifiers, could also be used to display the HFDF counter record. In this application, several successive scans of the counter could be presented simultaneously, and the shift in count trends could be easily noted.

In 1953, the author proposed a system for rapidly presenting the stroke repetition rate on an oscilloscope. The present HFDF counter requires a full six minutes for completing such a display. The proposed system exhibited a counter display at a 1-cycle per second rate.

The presentation from a direction finder is focused on a television camera tube which exhibits storage characteristics. At the end of a one-second exposure, the electron gun of the camera scans an annular region about the origin of the imaged direction finder display. During the circular scan, the camera tube signal varies according to the stroke intensity at each point along the path of the scan. The circular scan can be made to move at constant angular velocity about an origin that corresponds to the origin of the direction finder presentation. Thus, the camera tube signal contains the information relating the stroke count to azimuth. When the camera signal is presented as a function of time, it also represents the count as a function of azimuth.

A full second is allowed for the storage of count on the face of the camera tube. The single circular scan at the end of this exposure

period takes place in one-13,500th of a second. The basic television synchronizing generator circuits can be used to obtain the two 13,500-cycle sine waves required to perform the single circular scan.

The Memo-Scope can be used to advantage to display the output from the above high-speed counter. A permanent record can be obtained by photographing the display as presented on a conventional cathode-ray tube.

The strides that have been made toward the instantaneous evaluation of a severe storm are indeed encouraging. The present tracking method could be improved by the addition of a few time-saving features that would allow the operator more speed in procuring data for immediate evaluation. The acquisition of the above mentioned equipment would allow the operator additional time to draw conclusions concerning the direction of travel and the severity trends of a storm. It is hoped that someday it will be possible to use the early evaluation of a tornadic-prone storm center and take cloud seeding measures that will completely disperse the tornadic tendency.

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## VITA

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