DEVELOPMENT OF A HIGH SPEED LIGHTNING CAMERA

By

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PREFACE

My years of association with research at Oklahoma State University on atmospheric electricity, especially as it occurs in connection with severe thunderstorms, has been rewarding in many ways. This is a very interesting area, and yet it is surprisingly little known. I know of no tutorial book in the field which can be regarded as representing satisfactorily the ideas of modern investigators.

It is, at the same time, a very basic field; weather has a profound effect on men and their civilizations.

Few people realize how important a role electricity is suspected to play in meteorological processes, but there have been recently advanced serious proposals that electrical effects may cause, under at least some conditions, rain, wind, and tornadoes. It is, of course, undisputed that electromagnetic transients occurring as a result of lightning activity may be used to effectively locate electrically active storms.

The instrument described in this thesis, the periscope camera, has already proven its ability to produce detailed and reliable evidence about the position and timing of visible lightning. It is clear that it will be used in this capacity for many years. In consideration of this, I have endeavored in writing this thesis to produce a document which will be useful to whomever has the responsibility for operating and maintaining the periscope in the future.

Many people have helped with the periscope and this thesis, and I wish to take this opportunity to thank them. Gary Richardson, Harvard Tomlinson, and Johnny Duncan did the electrical wiring, electronic unit construction, preparation of wiring diagrams, and preparation of working drawings for the machine shop projects. Ray Calkins offered several helpful suggestions and proofread the manuscript. Dr. Charles B. Moore and Dr. Paul Silberg encouraged me to write on the periscope. I appreciate the contributions of all these individuals very much.

My wife, Jane, is deserving of special thanks both for her encouragement and for her work transforming my dictation into this thesis.

Special thanks goes to Dr. Herbert L. Jones for his continuing support, inspiration and encouragement in every problem encountered.

TABLE OF CONTENTS

LIST OF PLATES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Research on electrical effects of severe weather, particularly thunderstorms, has been in progress at Oklahoma State University for many years. This research has consisted chiefly of the observation of thunderstorms by radar and the recording of electromagnetic effects of lightning discharges. Transient electromagnetic radiation caused by lightning discharges is termed atmospherics, which is usually shortened to sferics.

Sferics are most frequently recorded using an instantaneous radio direction finder[1]. An instantaneous direction finder is a radio receiver which permits the determination of the direction of a received signal instantly. This is obviously not possible with the conventional direction finder, where one rotates an antenna and observes its orientation when a null is observed. The instantaneous feature permits the direction finder to be used with transient signals such as sferics radiated from lightning. Such a direction finder usually consists of at least two separate receiving antennas, oriented so that their patterns do not coincide. The orientation is such that, in general, a signal from a given direction will produce certain

[1]An excellent general treatment of such receiving systems may be found in Donald R. Rhodes, Introduction to Monopulse (New York, 1959)

amplitudes at the inputs of the two receivers connected to these two antennas. A signal of the same magnitude from a different direction will produce different amplitudes at the receiver inputs. In this way the relative amplitude of the signals from the two receivers will provide information on the direction from which the pulse was received. For sferics work, the most common practice is to use two loop antennas, placed at 90° to each other. The output of one of the loop receivers is applied to the horizontal deflection plates of an oscilloscope, and the output of the other is applied to the vertical deflection plates of the oscilloscope.

If the gains of both channels are equal and the antennas are identical loops or adcocks set at 90° to each other, we may say

$$A = K \cos \theta$$

$$B = K \cos (\theta - 90°) = K \sin \theta$$

where A is the signal amplitude of the channel placed on the horizontal deflection plates, B is the corresponding quantity for the vertical deflection plates, K is a constant whose value depends on the signal and the system, and θ is the azimuth from which the signal was received. When these in phase signals are added vectorially on the screen on the oscilloscope they will form a line. The inclination of this line, ϕ, will be

$$\phi = \arctan (B/A)$$

$$\phi = \arctan (\sin \theta/\cos \theta) = \arctan (\tan \theta)$$

$$\phi = \theta.$$

Therefore, the inclination of the line on the oscilloscope screen will be the azimuth from which the signal arrived. That is, we may calibrate the oscilloscope screen in degrees and then read the direction from which our signal came directly.

One problem still remains, however. The line whose inclination we are reading extends in both directions from the center spot on the cathode ray tube screen, thus producing a 180° ambiguity in direction. This may be eliminated by providing a third receiver channel, this one using a vertical antenna. The output of this third channel is shifted in phase 90° so that it will be in phase with the loop signals, then applied to the control grid of the cathode ray tube. This will result in the cathode ray tube trace being intensified as it deflects in one direction from the central dot, and as it deflects back in the other direction it will be blanked out. However, if the sferic had been from a direction 180° removed from the one just considered, the loop signals would both be reversed in phase by 180°, but the signal from the vertical antenna would not be changed. Therefore a deflection from the central spot in the opposite direction would be observed on the cathode ray tube. In this manner the 180° ambiguity is eliminated.

At Oklahoma State University, two separate direction finders of this type have been in use for many years. One of these operates at a frequency of ten kilocycles; the other operates at 150 kilocycles[2,3].

Another quantity which has been recorded here is a broadband waveform of the individual sferic. This normally consists of the output from a vertical antenna, passed through a wideband amplifier

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[2]Ruben David Kelly, "Development of Electronic Equipment for Tornado Detection and Tracking," (Ph. D. Dissertation, Oklahoma State University, 1957).

[3]Donald Charles Scouten, "The Development of an Improved 150 Kilocycle Instantaneous Sferic Direction Finder," (Master's Thesis, Oklahoma State University, 1960).

and displayed as a transient wave form on an oscilloscope with triggered sweep. The bandwidth covered by this equipment at Oklahoma State University is about 3 to 270 kilocycles. Recordings showing slower variations of the vertical component of the electric field have also been made; these normally consist of the voltage induced on a vertical antenna or some other elevated conductor supported on an insulating structure. The output from this is also passed through a broadband amplifier then recorded on either a strip-chart recorder or on an oscilloscope, using continuous motion film to provide the sweep. This provides a continuous record in time, without interruptions due to oscilloscope retrace.

These recordings have been made for both near and distant storms.

Some very useful information which has not been reliably recorded heretofore is the nature of the lightning strokes which are causing the observed sferics. It would be desirable to know whether a lightning discharge was cloud to cloud or cloud to ground. A lightning stroke might be large, small, or might fill the entire sky with a dramatic curtain of interlaced discharges. The stroke path could be chiefly horizontal, vertical, or anything in between.

It would also be useful to know the spatial location of the stroke channel; for example, this could be expressed in spherical coordinates, in which case we would have an azimuth, an angle of elevation, and a range for each point of the stroke channel.

A lightning stroke does not normally consist of a single discharge. Rather, it usually consists of a number of discharges along the same or similar ionized paths. These individual discharges are referred to as return strokes.

The various return strokes that make up a lightning stroke usually follow the same path, but not always. In some cases return strokes will be observed to depart from some portion of the path followed by their predecessors. Also, it is not unusual for the first return stroke of a series to cause current through channels which are not used appreciably on subsequent return strokes. These often take the form of small side streamers perhaps 300 to 500 feet long, and extending down from the main stroke path[4]. They are often referred to as ramifications.

It is not unusual to observe variations in relative current density in various parts of the channel from one return stroke to another[5].

Another very interesting feature of lightning strokes about which comparatively little is known is the leader. It appears impossible for a discharge path in a gas to break down uniformly along its length. Rather, it is necessary that some type of leader discharge precede the main discharge. The currents involved in this leader discharge are small compared to those in the main discharge.

A leader might be characterized as the propagation of an ionized region in the gas in which the discharge is about to take place. In long laboratory spark discharges, the leader is observed to begin at one of the terminals and propagate to the other. As soon as it reaches the other, an ionized path exists between the two. The main discharge then occurs over this ionized path. Apparently the gas is not readily

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[4]This effect is illustrated and discussed in chapter VI.

[5]Ibid.

ionized without the aid of the high field which can exist at the front of an advancing column of ionized gas.

Several types of leaders have been observed in connection with lightning strokes. Of these, the best documented is the one known as the stepped leader[6]. In a stepped leader, the ionization advances in short steps; there will be current flow and a short length of path perhaps fifty feet long is ionized. There is a pause, then current flows again through the portion that has already been ionized and about fifty feet beyond. Then there is another pause, after which current flows again through the section which has previously ionized and a new step is ionized. The ionization of these different steps occurs on the order of ten microseconds apart.

The stepped leader channel is luminous when a current pulse flows through it. The newly ionized segment of the path glows most brilliantly, and the rest of the path glows more dimly.

The entire stepped leader process requires on the order of five-hundred microseconds to a millisecond for completion.

Many of the phenomona observed in lightning discharges have never been observed in a laboratory spark discharge. This is not surprising, since the conditions under which laboratory spark discharges occur are so much different from those involved in a lightning discharge. Laboratory spark discharges are seldom obtained over distances of more than twenty or thirty feet. Lightning strokes, on

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[6] B.F.J. Schonland, D.J. Malan, and H. Collens, "Progressive Lightning II," Proc. Roy. Soc., (1935), pp. 595-625

the other hand, occur over paths many thousands of feet long. This indicates that the potentials associated with the lightning stroke are much higher than anything humans have yet generated.

Another consideration is that a lightning stroke is actually discharging a space charge. This is another feature that is not readily duplicated in the laboratory.

Another interesting occurrence that is sometimes observed in lightning strokes is the continuous flow of current for a period of time as long as many milliseconds, as contrasted to the usual flow of current in pulses of less than one millisecond duration. These longer current flows have been observed by several investigators[7] and they have been associated with characteristic electric field records.

In view of the complexity of single lightning strokes, it is desirable to have additional information to correlate with the electromagnetic field recordings, if we wish to learn as much as possible about the observed lightning.

It would be useful to record the exact time of each return stroke, the leader type, the time of the leader, the current involved, and unusual features such as ramifications or continuous current flow for some periods of time.

A reasonably simple way of recording some of this information is to use a camera in which either the lens or film is moved continuously. In this way the return strokes will be separated on the film and will not fall on top of one another. The separation will give the time

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[7]This effect is illustrated and discussed in chapter VI.

interval between the return strokes. Luminous leader phenomena will also be visible. If current persists in any of the channels after the return stroke, this will be visible as a smear extending away from that return stroke in the direction of image motion relative to the film.

If means are provided for recording the orientation of the camera, the azimuth and elevation to each point on the stroke path will also be available. The range may be roughly estimated from a photograph also, since the cloud base height can be determined approximately from meteorological data.

It will be apparent in a photograph whether a stroke is from cloud to ground or cloud to cloud, and whether it is large, small, or covers the entire sky.

At the time this problem arose a surplus periscopic aircraft gun sight was available. It could be rotated 360° in azimuth and $\pm$ 90° from the horizontal in elevation. The end of the periscope was sealed with an optically flat window, inside which was a scanning prism mounted before an objective lens. Rotating a shaft which ran down through the periscope to a manual control made it possible to change the elevation of the field. It was in good condition, but the eyepiece was missing; it had apparently been salvaged many years ago.

A camera which is to be used to photograph lightning strokes during a thunderstorm faces some obvious problems with respect to weather-proofing and operator comfort and convenience. To most readily overcome these problems a periscope camera which could be operated from inside the atmospherics laboratory and yet photograph any part of the sky would be desirable. In view of this fact, it was determined to construct a camera using as the objective lens system the optics of the surplus periscope.

CHAPTER II

FUNCTION OF THE PERISCOPE CAMERA

Each time a lightning stroke occurs within the field of view of the periscope its luminous paths are recorded on the film. The film is moved continuously at a constant velocity, and there is no shutter in the optical system. As a result, a continuous light would appear as a streak on the film. Most lightning strokes, however, do not produce a continuous glow of light. Rather, they consist of a number of discharges along similar, but not necessarily the same, ionized paths. The pulse of luminosity from each of these discharges normally lasts less than a millisecond. As a result, the lightning stroke paths will be recorded on the film without appreciable film motion occurring during the time the luminosity of the lightning stroke is high enough to cause recording on the film. Therefore the lightning stroke will not appear to be blurred.

The successive discharges occurring over the same path will appear beside one another, and the distance of separation between them will provide the time difference between them. Time marks, consisting of a digital clock face which will be recorded once each six seconds, a one second flashing light, a one tenth second flashing light, and a one hundredth second flashing light are also recorded on the film. The time standard for the clock and the one, one tenth, and one hundredth second pulses are obtained from the laboratory master timing system, so that periscope camera timing will always be in exact synchronism with that of the other recording cameras.

The periscope camera can be rotated 360° in azimuth, and the elevation of the center of the field may be varied from less than 0° to 90° with respect to the horizontal. Each time the digital clock face is recorded, dials showing the current azimuth and elevation of the periscope's field of view are also recorded.

The operator is able to see the entire field of view of the camera at all times, and by pressing a button he may also see the time, azimuth, and elevation.

Occasionally current flows for a longer period of time than normal in a return stroke. When this occurs, it is recorded as a broadening of the stroke path in the direction of film motion.

A reticle, consisting of three concentric circles with a dot at their common center, has been placed in the periscope optical system. This reticle is therefore seen superimposed on the image of the scene outside provided by the periscope. Whenever there is a lightning discharge in the immediate vicinity of this reticle, it is recorded stroboscopically in its current position on the continuously moving film.

This will permit the accurate determination of the time of occurrence, elevation of any part of the stroke path, and azimuth to any part of the stroke path, for any stroke which illuminates the reticle sufficiently to record any part of it on the film. Knowledge of where the stroke is in the field is obviously necessary to determine the azimuths and elevations, but why this knowledge is necessary to determine the exact time of occurrence is not so obvious. However, with continuous motion film it can be seen that two separate strokes occurring at the same time will be recorded at different places on the film. It is therefore necessary to know where the stroke is located in the field of view to determine its time with maximum precision.

If it is not known in what part of the field a stroke occurs, and it is assumed that it occurred in the center of the field, the maximum time error is $\pm \frac{1}{2}$ the time required for the film to move the width of the camera field stop. If the stroke follows an irregular path and none of the path is obscured by the edge of the field, the possible error is reduced somewhat. If part of the path is obscured by the edge of the field, it is then possible to determine the time with maximum accuracy.

The reticle may also be used by the operator to take bearings or to determine what is optically visible at a given bearing such as one from which heavy or unusual sferic activity has been observed. The reticle may be illuminated with variable intensity at the option of the operator. This makes taking bearings or observing a given bearing possible at night as well as during the day.

An analysis of the periscope camera film permits the determination of the time of each return stroke, any variations in path from one return stroke to another, and the existence of any sidestreamers. With some return strokes, the existence of variations in current along the channel from one current surge to another is recorded. Useful information is also provided relative to the spatial orientation of the stroke path. It is apparent whether a given stroke is from cloud to ground, or occurs between space charge regions in a thunderstorm.

The periscope camera now makes it possible to obtain accurate information about many characteristics of lightning strokes which were formerly guessed at or completely unknown.

CHAPTER III

OPTICAL SYSTEM

The Periscope Optics

Light from the lightning stroke will enter the periscope through a scanning prism which may be rotated mechanically about a horizontal axis. As shown in figure 1, rotation of the scanning prism in this way permits selection of a given ray of incident light as the one which emerges going directly down into the objective[1], i.e., as the one in whose direction the periscope is pointed. The net effect of this is to permit variation of the elevation of the center of the field of view by rotation of the scanning prism.

The objective will form an inverted real image in the plane of the reticle plate. As a result, the reticle will be superimposed on the image, and both will serve as an object for the erector[2]. The erector will produce an upright real image at a point falling inside the beam splitting prism.

The converging light from the area toward which the periscope is directed enters the beam splitting prism from the top. When this

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[1]Although the various optical elements are drawn and referred to as a single simple lens, it is understood that they all are coated achromats, each consisting of from three to eight glass elements, with all air to glass surfaces coated.

[2]Ibid.

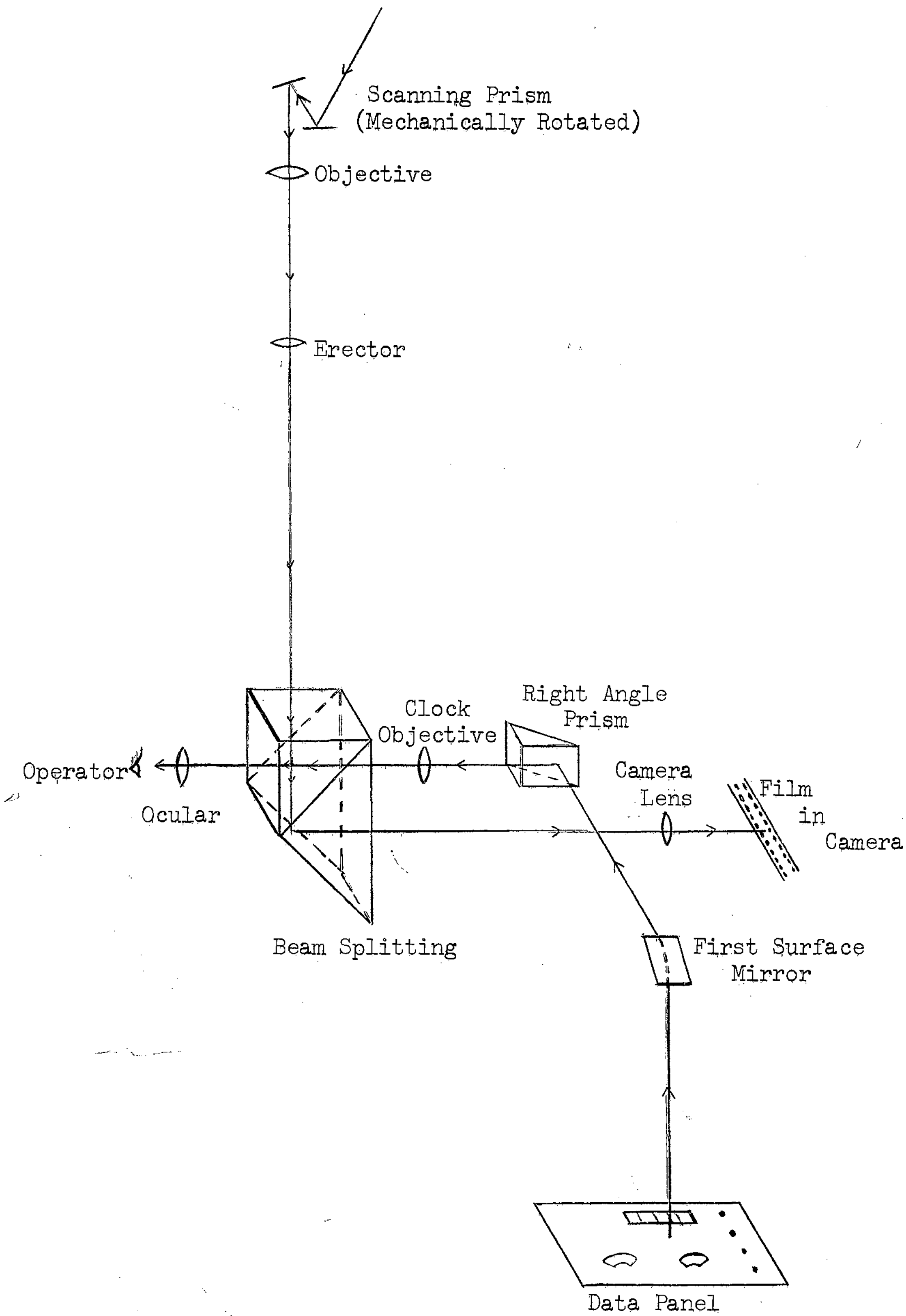

Figure 1. Optical System Diagram

converging light encounters the beam splitting surface, part of it is reflected to form a real image in the plane of the eyepiece field stop. This image is seen by the operator through the ocular[3]. The eyepiece field stop is rectangular and has been shaped to limit the field seen by the operator to exactly that field of view covered by the camera.

The converging light from the scene outside which is transmitted by the beam splitting surface in the beam splitting prism forms a real image of the scene in the lower part of the prism. Diverging light from this image is totally reflected from the right angle face of the prism and proceeds into the camera lens[4], which forms a real image of the same scene on the film. The film is moved horizontally at constant velocity so that the time of occurrence of any lightning stroke can be determined when its position in the field of view is known. The position in the field will be known for almost any stroke recorded, since the reticle will be recorded each time a lightning flash crosses it. Any stroke of which an appreciable portion is recorded and which misses the reticle will almost certainly intersect the edge of the field. This will serve to fix its position in the field.

The Data Panel Optics

When the data panel is illuminated by the stroboscope tube or a neon flash occurs on it, the light from it goes up and is reflected from the first surface mirror into the right angle prism. It is then

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[3]Ibid., p.13.

[4]Ibid.

totally reflected from the 45° face and proceeds out of the prism and into the clock objective[5]. Plate I, a photograph taken through the flange where the first surface mirror housing attaches, shows the right angle prism and clock objective mounted in the periscope. The camera lens and mount are visible in the lower part of the photograph.

Converging light from the clock objective enters the beam splitting prism and encounters the beam splitting surface. Part of this light is reflected downward. This light forms a real image in the prism coincident with the image from the outside scene. Light from the image of the data panel is then made to form a real image on the camera film by the same optical components that accomplish this for the image from the scene outside. Consequently, the data panel is superimposed on the outside scene.

The light from the clock objective that passes through the beam splitting surface goes on out of the prism and forms a real image in the plane of the eyepiece field stop, which is the plane of the image of the scene which is seen by the operator through the eyepiece. The data panel is thus seen by the operator superimposed on the outside scene whenever the data panel is continuously illuminated.

An incandescent lamp controlled by a push button switch is provided so that the operator may view the data panel whenever he wishes to determine the azimuth, elevation, or time.

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[5] Ibid., p.13.

PLATE I INSIDE THE PERISCOPE

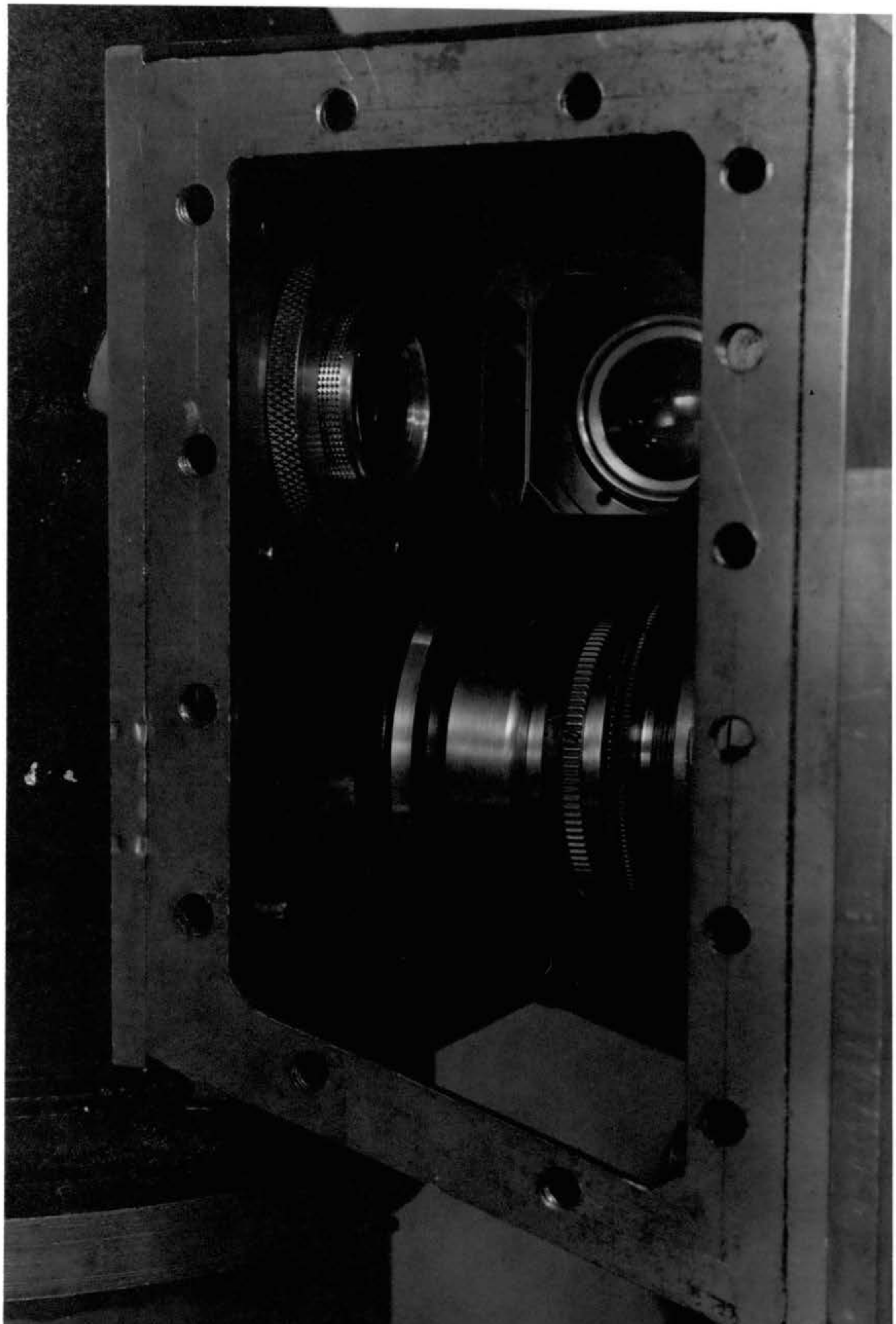


Plate II shows the camera with lens and locating studs mounted. The lens mount spacer is in segments, making it possible to place the lens anywhere from its normal position on the camera to 3.62 inches forward of this position. A set of shims, one of which can be seen on the camera, make possible the modification of the mounting position of the camera. These two adjustments make it possible to vary the magnification of the periscope camera if this is desired.

The rectangular box at the bottom of the large cylinder visible on the complete periscope in plates III and IV contains the data panel. The rather large length of optical path from the data panel to the image of the data panel on the film is necessary to obtain a sufficiently small image of the data panel on the film since a minimum limit of about 90 mm focal length is placed on the clock objective by the physical size of the beam splitting prism and the position of the image within it.

The Camera Lens

The camera lens is a special high speed lens, corrected for use at a one-to-one object-to-image ratio. Most high speed photographic objectives are corrected for use at some distance greater than fifteen feet. This is typical since most photography done with high speed lenses involves subjects beyond fifteen feet. If such a lens is used at a one-to-one object-to-image ratio, or very close to this, definition will be seriously impaired. For this reason, the lens which was originally used with the oscilloscope camera would not have been very satisfactory. It was therefore replaced with a special Carl Myer 1:1 high speed objective. This lens has a 40 mm

PLATE II CAMERA WITH LENS AND LOCATING STUDS MOUNTED

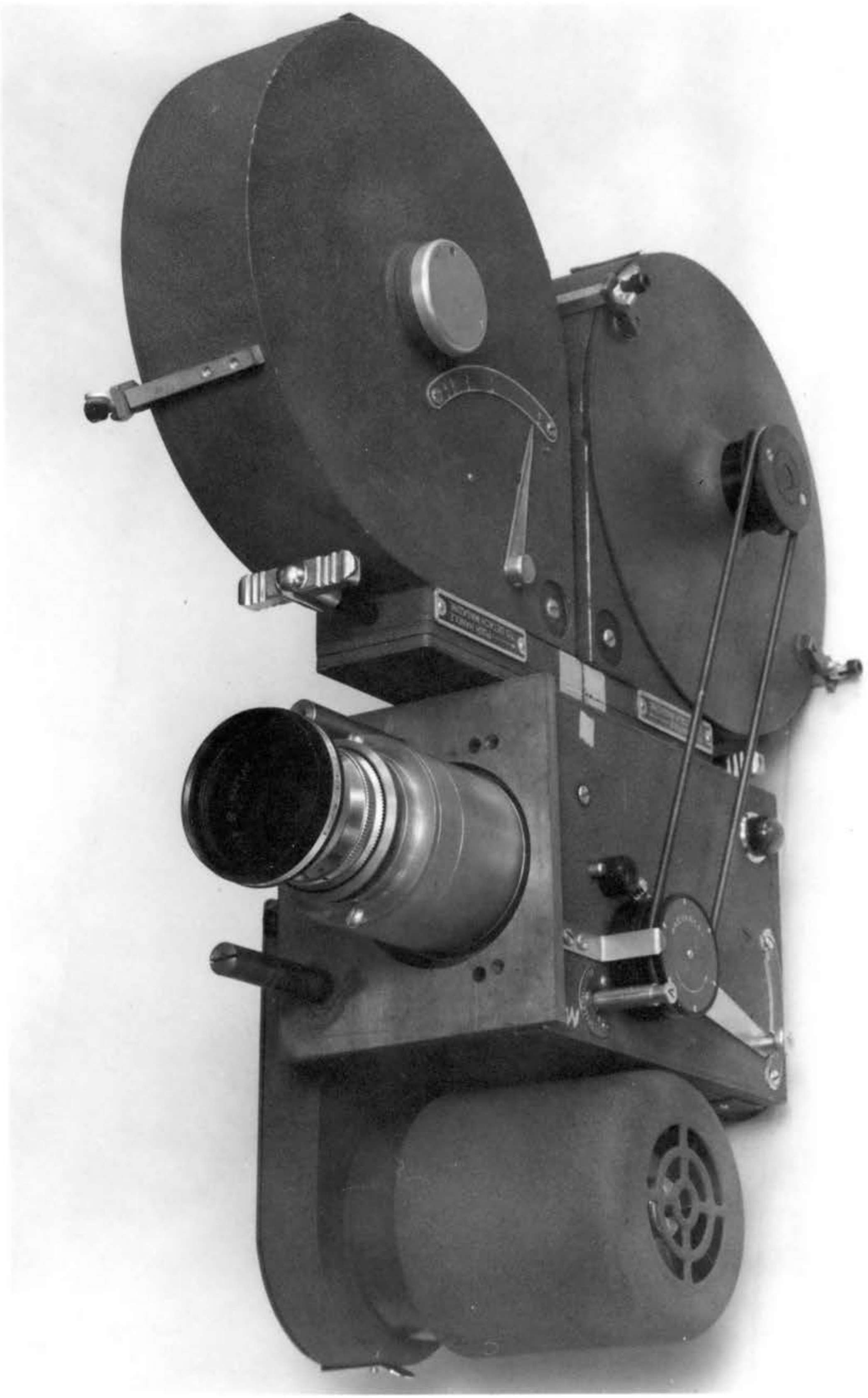


PLATE III THE PERISCOPE CAMERA

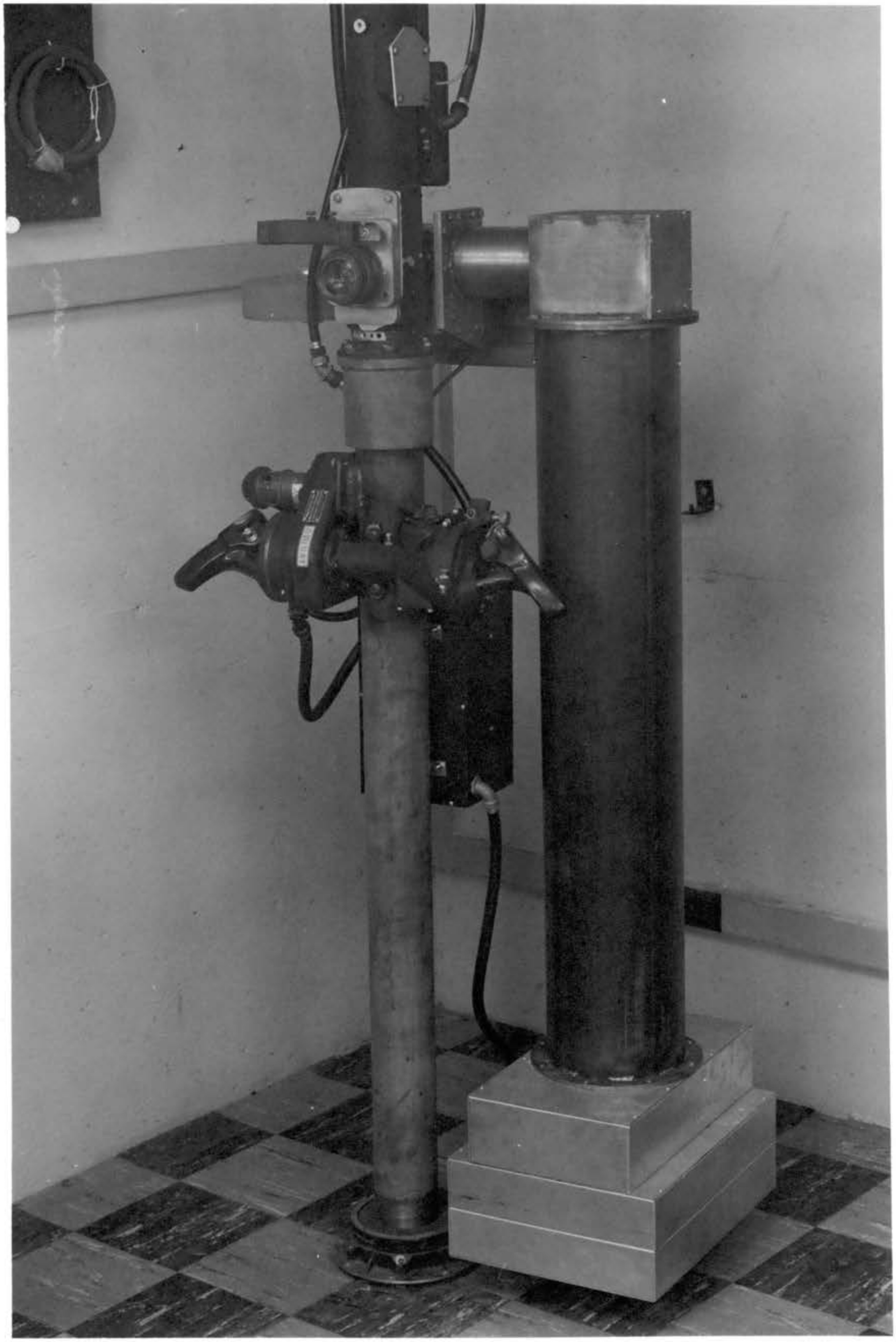
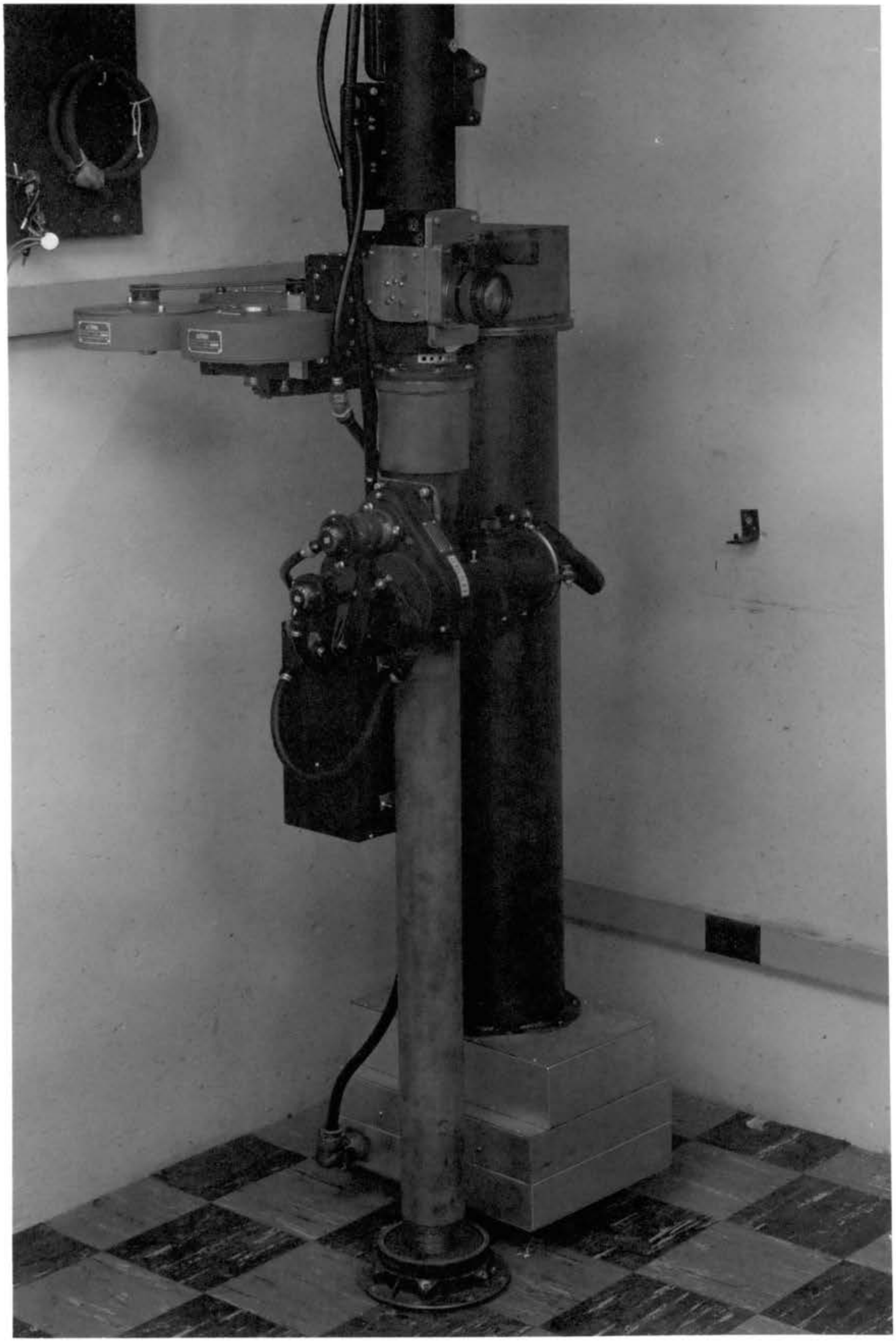


PLATE IV THE PERISCOPE CAMERA



focal length, a speed of f 1.4, and is corrected for use at a one-to-one object-to-image ratio. It was purchased commercially, and is the most expensive component in the periscope.

The Camera

The 35mm continuous motion film camera used on the periscope is a modified DuMont 321-A Oscilloscope camera. By shifting gears, it is possible to vary film speed in this camera from .6 inches per minute to 10,000 inches per minute. It is powered by a synchronous motor; therefore distance and time may be regarded as proportional anywhere along the film except while the motor is starting or stopping.

The film gate field stop on this camera is normally a 23mm diameter circle. This was not satisfactory for the periscope, so it was modified to a 24 x 36mm rectangle.

This 321-A camera also has its clutch permanently locked in the engaged position.

One of the most important advantages of the 321-A camera, aside from the very wide range of film speeds available, is the ready interchangability of film magazines. These will hold a maximum of four hundred feet of thirty-five millimeter film, and both takeup and supply magazines can be rapidly and easily interchanged under normal room illumination.

Use of Infrared Film

The objectives to be realized in lightning photography require maximum penetration through clouds and precipitation with good definition. High optical and film emulsion speed is desirable to permit satisfactory recording of relatively low luminosity channels.

It is planned to experiment with Eastman Kodak's High Speed Infrared film, used with a Wratten G filter.

Infrared should give better cloud penetration[6] and reduce extraneous illumination from skylight during daytime storms when the clouds are to the west in the afternoons and the sky is relatively clear to the northeast. Skylight contains very little infrared radiation.

The Periscope Camera Mount

The head of the periscope projects through a steel plate set in the roof of the atmospherics laboratory. The scanning prism and objective of the periscope are protected from the weather by a hermetically sealed cast aluminum cover, which has an optically flat glass window set in it at a 45° angle as shown in plate V. The scanning prism is placed so that as it is rotated the field of view is through this glass window.

The rotation of the scanning prism, and thus the elevation, is controlled by a shaft running up the periscope tube beside the optics. This shaft is rotated by rotating the handles held by the operator, visible in plates III and IV. This permits the operator to vary the angle of elevation at will.

The periscope is supported at top and bottom by two large ball bearings. The top one is mounted in a flange which is sealed weatherproof to the plate set in the roof. The bottom bearing is mounted in a

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[6]D. M. Gates and C. C. Shaw, "Infrared Transmission of Clouds," _Journal of the Optical Society of America_, V.30, No.9, (Sept. 1960), pp. 876-882.

PLATE V THE WEATHERPROOF PERISCOPE HEAD (FULL SIZE)

stationary flange which is bolted to the floor of the atmospherics laboratory. This supports the periscope solidly yet permits 360° rotation.

Two selsyns are geared to the azimuth and elevation controls, and two others, driven by these, operate the azimuth and elevation dials on the data panel. All electrical connections are brought out through slip rings, permitting unlimited rotation of the periscope.

Adjustments and Alignment of the Periscope Optics

The camera lens focus setting for which best results with Tri-X film are obtained is twenty-seven half turns from the position where the lens is screwed completely into the camera. The clock focus setting for Tri-X is $8\frac{1}{4}$ quarter turns from the position where the clock objective is screwed entirely into the periscope. With High Speed Infrared film, the camera lens should be set thirteen half turns from the camera. The clock focus is fair without any changes, but before any serious work with High Speed Infrared film a full scale test should be made to determine the proper position for this focusing control.

The camera image size can be modified within limits. Making this adjustment involves moving the camera further from or closer to the image which the camera lens is using as its object, and moving the camera lens relative to the camera and this image.

The camera itself is moved by the introduction of, or elimination of, shims between it and its mount. The shims currently available have a total thickness of some three inches and are adjustable in steps of 1/32 of an inch from zero to maximum thickness.

The camera is provided with locating studs which engage holes drilled in the metal plate on which it is mounted. This insures that the optical system will not be misaligned as a result of removing the camera. The position of the camera lens is controlled by a threaded focusing mount mounted on a set of interchangable spacers.

The combined effects of the focusing mount and the spacers make it possible to move the camera lens more than four inches with respect to the camera. Additional spacers may be inserted behind the camera lens, or removed from it, by removing the camera and then removing the screws which hold the camera lens mount to the camera.

If it were desired to make the image on the periscope film larger, this would be accomplished by moving the camera further from the periscope. This would involve the insertion of additional shims between the camera and the plate on which it mounts. For this same case, shims would be removed from the camera lens mount. This would move the camera lens closer to the camera.

The image on the camera film is now approximately 1.2 times as large as the image in the beam splitting prism, which is the object for the camera lens. Departure of much more than this from the one-to-one image-to-object ratio for which the lens was designed will impair definition seriously. Also, if it were attempted to enlarge the camera image by any great amount, the camera would be moved so far from the periscope that it would strike the wall when the periscope was rotated. This would be an intolerable situation.

It is therefore apparent that any extremely large change in the optical magnification of the image on the film in the camera would involve changing camera lenses. Also, the image which serves as object for the camera lens is not of sufficiently good definition to permit much improvement from an enlargement of its contral section. If a small change is needed in the camera image size, it may readily be obtained in this manner, however.

Another change which should be made if the camera image size is changed is a modification in the eyepiece field stop. This stop, located immediately behind the eyepiece, limits the field of the eyepiece to coincide with that of the camera. To change it, after the camera field has been set as desired, a still exposure should be made of the terrain surrounding the atmospherics laboratory. This may readily be done in daylight by fitting the camera lens with a filter which will decrease the exposure time to a second or more, then introducing some opaque object into the path of the light which forms the image on the film, running the motor a few seconds to advance fresh film into the gate, removing the opaque object, allowing an appropriate exposure, then replacing the opaque object, and running the camera until the film so exposed is safely in the takeup magazine. This may be processed, and a print made. From this print it will be apparent exactly what field the camera covers. The print may then be taken out to the laboratory, and used as a guide in the mechanical modification of the field stop for the eyepiece.

Another set of optical adjustments which might someday be necessary are those associated with the data panel.

The simplest and most straightforward of these is the data panel focusing control. The data panel objective is the only other lens in the periscope in a focusing mount aside from the camera lens. It is set to give a sharp image of the data panel on the film.

The position of the data panel in the field of view of the periscope may be adjusted also. This adjustment is accomplished in several ways. The first surface mirror, mounted in the approximately cubical housing at the top of the large column having the data panel at its bottom is in a three point suspension adjustable mount. The two adjusting screws on this mount may be turned to change the position of the data panel in the camera field. This adjustment should be undertaken with care, since, due to curvature in the field, refocusing of the data panel objective will be necessary after it has been done. If desired, this mirror and its mount may be removed from the periscope by simply picking it up and removing it. It is held in place by gravity only. Picking it up and removing it in this way will not destroy its adjustment. Only loosening the lock nuts and turning the adjusting screws will change the adjustment of the mirror.

The first surface mirror should never be touched on its silvered surface. If it is planned to clean this mirror great care should be used. First surface mirrors are very readily damaged. The only way it should be cleaned is by very gently brushing it with a soft camel's hair brush. If such a brush is not available the mirror should not be cleaned. It is better dirty than scratched. In extreme cases first surface mirrors may safely be washed in water or soapy water, but here again it should not be touched with anything but a soft camel's hair brush.

The right angle prism located immediately above the camera lens may be rotated about a vertical axis by loosening the screws holding it to its mount. This permits movement in another direction of the data panel image.

The combination of adjustment of this prism and adjustment of the first surface mirror make it possible to place the data panel anywhere in the right hand two-thirds of the periscope field.

The combination of these two adjustments does not necessarily make it possible to place an erect image of the data panel anywhere in this region. On the contrary, when the first surface mirror is adjusted, the image of the data panel will be observed to rotate. This is due to the relatively complex movement of the first surface mirror. It does not simply rotate about one axis, but rather about three simultaneously, in combination with a displacement.

In order to correct the rotation of the image introduced by the adjustment of this mirror it is necessary to rotate the data panel itself. This may easily be done. The self tapping sheet metal screws holding the top of the data panel housing to the large cylindrical column above it are first removed. The data panel is then rotated until its image is upright, then new holes are drilled and the self-tapping screws are replaced.

CHAPTER IV

PERISCOPE CAMERA ELECTRONIC SYSTEMS

The Timing System

The data panel will be illuminated periodically by a stroboscope tube operated by the six second pulse from the master timing system. Neon bulbs located on the data panel will be flashed once each second, one-tenth second, and one-hundredth second. They will be controlled by available timing waveforms from the master timing system.

The time standard for the laboratory timing system is a one hundred kilocycle standard frequency crystal oscillator, designed by the National Bureau of Standards. This oscillator is in a hermetically sealed brass case. The complete oscillator is in an oven, the temperature of which is very closely controlled.

The oscillator, as is the entire timing system, is completely transistorized. Its tuning control is operated by a servo motor controlled manually from the frequency divider and amplifier unit. The oscillator is tuned by zero beating against WWV using a lissajous pattern as indicator.

The one hundred kilocycle output from the oscillator goes through a series of digital countdowns, which produce frequencies of one hundred cycles per second, ten cycles per second, one cycle per second, and one-sixth cycle per second.

The one hundred cycle per second frequency is used to drive the digital clocks and to provide synchronism for the one-hundredth second neons on the periscope camera data panel. The ten cycle per second frequency is used to provide the one-tenth second time marks on the periscope. The one second signal is used to flash the one second neon on the data panel, to flash the one second timing mark on the rack mounted recording camera, and to operate the counter on the portable recording camera. The one-sixth cycle per second output is used to flash stroboscope tubes illuminating the digital clock on the rack mounted recording camera and the data panel on the periscope camera.

The entire timing system is operated from a storage battery, which is continuously charged whenever line power is on. This permits reliable operation of the timing system during power failures, thus avoiding the problems which would be associated with its being out of service for a time.

Pulse Former and Amplifier

The one hundred cycle per second, ten cycle per second, one cycle per second, and one-sixth cycle per second outputs from the master laboratory timing system are square waves, having a peak to peak amplitude of five volts. There is a d-c level associated with them, but it is of no importance for the present purposes. The point in time in which we are interested is marked by the fall of the square wave; i.e., the fall of the square wave occurs at the even one second time, for example, for the one cycle per second wave.

The pulse former and amplifier circuit shown in figure 2 takes the waveform just described and converts it into a train of positive

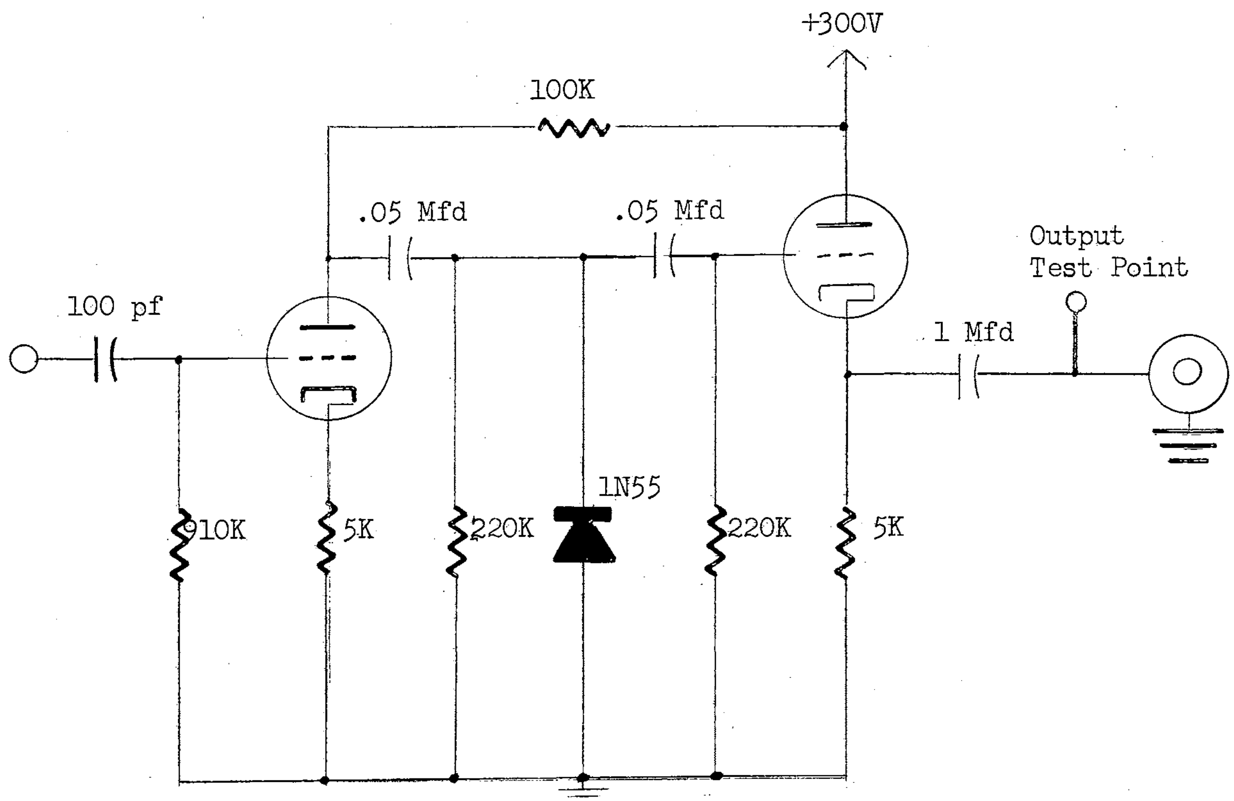


Figure 2. Pulse Former and Amplifier Circuit

spike pulses, each occurring at the time marked by the fall of its square wave, and provides a low impedance output for transmission to the periscope control unit.

The one hundred pf input capacitor of the pulse former and amplifier unit is a sufficiently small value to cause differentiation of the input waveform. This differentiated waveform is amplified by the first section of the 12AU7, and the output of this amplifier is a-c coupled to a pulse shaping network. The nonlinear element in the shaping network is a 1N55 diode connected between the signal line and ground with polarity such that the negative pulses will be eliminated.

The output of this pulse shaping circuit is a-c coupled to the second section of the 12AU7, which is a cathode follower. This provides a very low impedance output, so that the loading due to the long cable to the periscope control unit will not adversely affect performance.

Neon Driver Circuit

The neon driver circuit, illustrated in figure 3, has as input the pulses produced by the pulse former and amplifier circuit just described.

V1 a in this circuit is a conventional pulse amplifier. V2 a and b are connected as a monostable multivibrator. The function of the monostable multivibrator is to provide the proper waveform with which to fire the neon bulbs. It is triggered by a negative pulse applied to the grid of V2 a. When it is triggered, it produces an output pulse of approximately one hundred volts amplitude and five hundred microseconds duration.

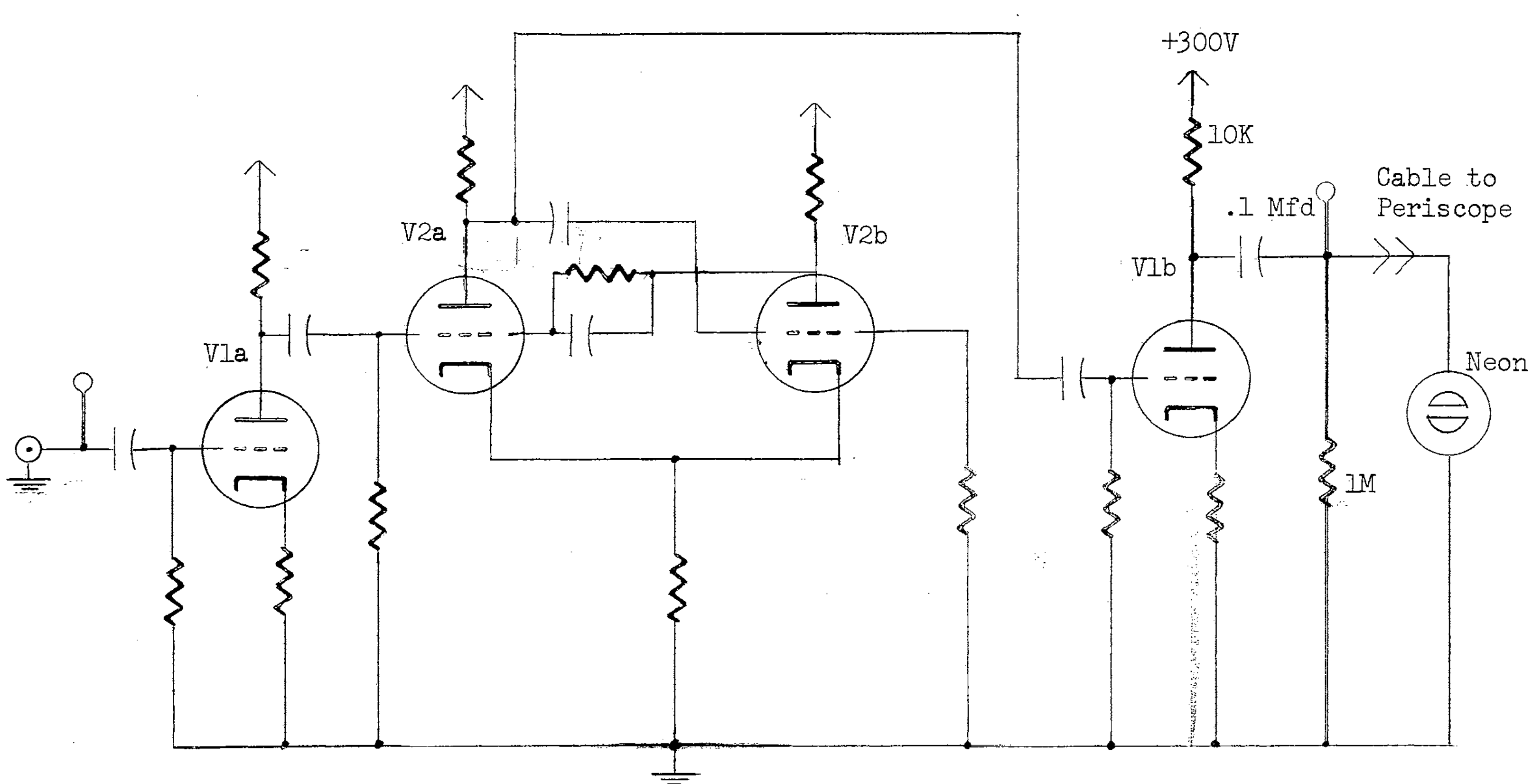


Figure 3. Neon Driver Circuit

Tube V1 b functions as a power amplifier, to drive the neon. This circuit produces good, crisp, brilliant flashes of the neon, with little afterglow.

An unusual difficulty was encountered when this circuit was being placed in operation. The difficulty observed was that the neon would flash repeatedly with no input being applied to the neon driver circuit. Checking in the circuit with an oscilloscope revealed that pulses could be found on all signal lines when the neon flashed, but, of course, this did not necessarily mean that the neon was firing as a result of a signal originating at the input. It might simply be picked up on the input from the output as the neon fired. The neon firing would involve high peak current which could easily result in pickup of pulses.

In an effort to determine whether or not the pulses were being picked up in the early sections of the neon driver circuit, tube V2 was pulled. The neon continued flashing. Tube V1 was then pulled. The neon still continued flashing. This was puzzling since the circuit now consisted of a 10 kilohm resistor, a .1 microfarad capacitor, and a neon bulb, all in series. This series combination was connected across a 300 volt power supply. That a completely series circuit of this sort could exhibit relaxation oscillation is not at all obvious.

Further investigation revealed that the .1 microfarad capacitor was actually acting as a resistor; its leakage current was responsible for the difficulty. The leakage current through this capacitor charged the stray wiring capacitance in parallel with the neon. When the stray capacitance charged up to a voltage above the ignition voltage of the neon bulb, the neon would fire. A resistance-capacitance neon relaxation oscillator was established using as the charging resistor a .1 microfarad capacitor and as the capacitor the stray wiring capacity of the cable to the neon bulb.

The problem was eliminated by connecting a 1 megohm resistor in parallel with each of the neon bulbs.

The Thyratron Controlled Stroboscope Circuit

The stroboscope tube used to illuminate the data panel each six seconds is the xenon filled high pressure three electrode type. High pressure, in this case, means a pressure of about ten torr. This pressure does not seem high for many purposes but is exceptionally high for a gas filled tube.

Such flash tubes are normally permanently connected to the capacitor which will discharge through them. This capacitor is then charged to the desired voltage. The flash tube pressure, however, is sufficiently high to insure that the flash tube will not conduct simply as a result of the applied voltage. The discharge is made to occur by the effect of a high voltage pulse, which is applied to an external third electrode on the flash tube. The high fields produced by this high voltage pulse cause the breakdown of the gas in the tube, with the resultant conduction by this tube of the charge on the main discharge capacitor.

The high voltage pulse for triggering this tube is normally provided by means of a special trigger transformer, through the primary of which a small capacitor is discharged.

A typical trigger circuit is shown in figure 4. Such a circuit is satisfactory whenever the flash tube is to be triggered by contacts

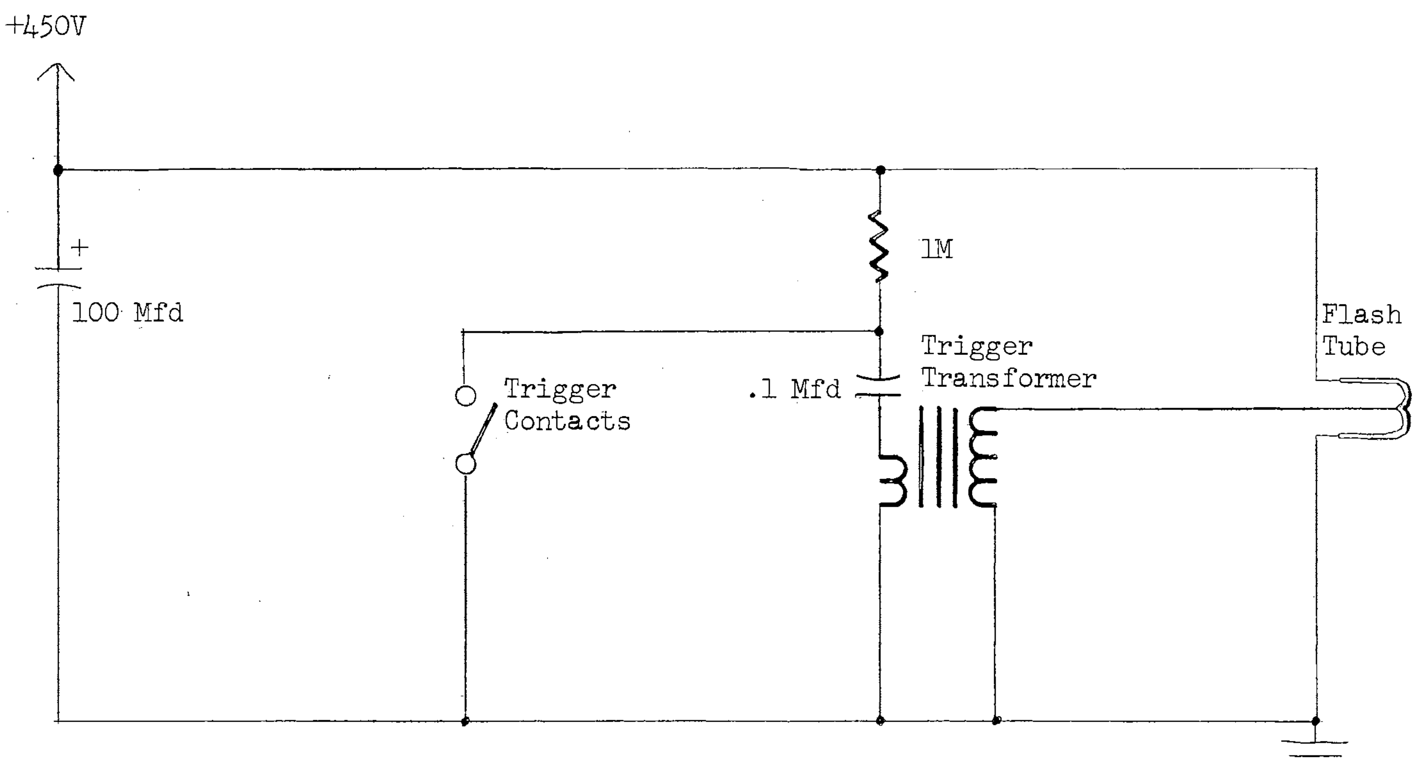


Figure 4. Contact Controlled Flash Tube Trigger Circuit

that will withstand the discharge current of the small capacitor. This might be the shutter contacts of a camera, for example, or the contacts of a switch or relay.

In order to trigger such a flash tube with an all electronic circuit, some means of switching the high peak currents involved in the discharge of the small capacitor must be utilized. One simple and readily available device which will do such switching is a small thyratron tube. The thyratron triggering circuit, shown in figure 5, is one example of a simple circuit which will trigger an electronic flash tube when a voltage pulse is provided to its input.

Since the thyratron conducts essentially no current before it fires, conventional cathode resistor biasing cannot be used. The thyratron used here, however, does require about seven volts negative bias on the grid. Rather than use a negative power supply to obtain this voltage, it was deemed simpler to use a 5.6 megohm resistor connected between B+ and the cathode of the thyratron to provide a bias current through the cathode resistor of the thyratron. Since the current through the thyratron is negligible unless it is fired, the 5.6 megohm resistor and the 135 kilohm cathode resistor plus part of the 25 kilohm potentiometer simply act as a voltage divider. They hold the cathode at approximately seven volts positive. The 100 kilohm resistor between the control grid of the thyratron and ground holds this grid at approximately ground potential, and the required -7 volts bias of the control grid with respect to the cathode is thus provided.

There is another problem if the thyratron, connected in this manner, is used as a switch. Its effective "turned on" resistance will still be slightly greater than that of the cathode resistor.

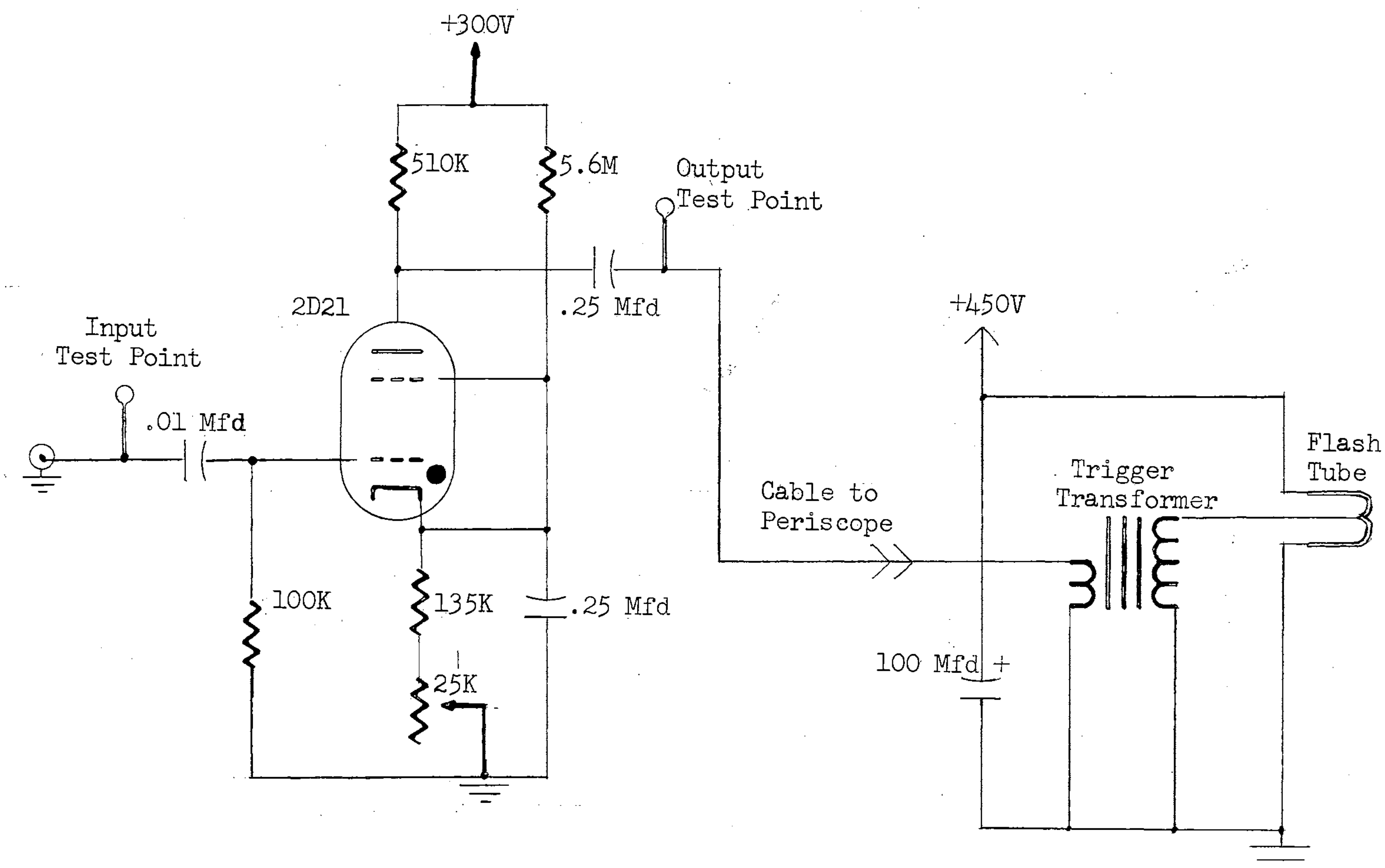


Figure 5. Thryatron Control Flash Tube Trigger Circuit

The resistance of the cathode resistor is much too great to permit in series with the thyratron in the present application, since rapid discharge of a capacitor through the primary of the trigger transformer is desired. It is therefore necessary to connect a large capacitor in parallel with the cathode resistance. When the thyratron fires, the charge which is initally on the .25 microfarad capacitor connected between the thyratron anode and the trigger transformer will be divided equally between that capacitor and the .25 microfarad capacitor in parallel with the cathode resistance. This will produce a current pulse through the primary of the trigger transformer. The high voltage pulse this produces across the secondary of the trigger transformer is sufficient to trigger the flash tube.

This, however, leaves the .25 microfarad cathode capacitor charged, but it will discharge rapidly as a result of the relatively low value of resistance in parallel with it. During the time that it is charged, the thyratron will not fire again because the cathode will be the capacitor voltage positive with respect to the grid. The time during which the thyratron will not trigger as a result of this will be a small fraction of a second, and this will cause no difficulty since the flash tube will only be triggered once each six seconds. The 25 kilohm potentiometer in the cathode circuit of the thyratron is provided to permit the trigger level of the thyratron circuit to be adjusted. This control should be set for reliable triggering from the normal source.

The Data Panel Digital Clock

The digital clock on the data panel will be driven from the one hundred cycle per second output of the master laboratory timing system which drives the digital clock in the rack mounted recording camera, since this unit is capable of driving two clocks.

By starting the periscope clock when its second wheel is in the same position as that of the other digital clock, both clocks can be set to the same time. After this is done, the clocks will always stay in synchronism, since they are synchronous motors driven from the same source. The clock on the periscope camera will therefore be corrected whenever the other clock is set.

In time, the clocks might drift out of synchronization slightly due to different rates of acceleration during times when the motors are slipping or when they are not energized. The motors will slip for a brief period of time after they are turned on, or after the advance-retard switch on the frequency divider and amplifier unit is operated. They would not be energized while turning, and thus might have different decelerations, immediately after they are turned off and before they coast to a stop. However, errors introduced by these effects would be small since the clocks are identical. If they occur, they could be corrected fairly easily by the same procedure used to synchronize the clocks originally.

Direct Current Power

The original periscope was equipped with a device known as a desiccator. The desiccator consisted of a 24 volt d-c motor which drove a small air pump. Air was pumped from inside the main periscope tube through a canister filled with calcium sulphate drying agent, and then was exhausted into the hermetically sealed housing of the scanning prism. Since this system provided a simple and effective way of defogging the optical flat which serves as the window for the scanning prism, it was retained.

Another useful feature of the original periscope which was retained is an illumination system for the reticle. The reticle illumination system consists of two grain of wheat bulbs, controlled by a rheostat-switch combination on the handles. All that was necessary to operate these lights was connection to a source of power. They were designed to operate from 24 volts, and the desiccator pump operates from 24 volts d-c.

It was therefore desirable to have a 24 volt d-c power supply on the periscope. Such a power supply was provided; it consists of a transformer providing 24 volts a-c and a full wave bridge rectifier, using 2 ampere silicon diodes. This power supply is located in the main junction box, designated "Big John" in the wiring diagrams in the appendix.

The primary of this transformer is energized whenever the rack mounted recording camera is plugged into its receptacle on the rack mounted equipment and the equipment power is on at the main breaker box. There are no switches in the primary circuit of the transformer, and it is normally energized continuously.

Recording Camera Power Control

There are three cameras at the atmospherics laboratory; these are the periscope camera, the recording camera permanently mounted with the rack mounted equipment, and the portable camera.

In connection with the installation of the periscope camera, the power wiring on these cameras was improved. There are now two active switches on each camera. One of these switches is in series with the motor of that camera and only that camera. The other is a main power switch for all cameras. Thus, to operate any or all of the cameras, the switches controlling the individual cameras that are to run are set on, and the switches controlling the other individual cameras are set off. Then any one of the other three switches may be used as a main power switch, since these three switches are all in parallel.

This permits easy control of recording from any position.

On the periscope, the master power switch for all cameras is a push button throw switch on the handles. It is conveniently operated with the left thumb. The switch which determines whether or not the periscope camera shall run when the cameras are switched on is either of the two switches on the left of the three in a row at the back of the camera. If either of these switches is up, the periscope will run when the main camera power is on.

The Servo System

Since the periscope was originally used as a gun sight, it was equipped with selsyns to give its position. These selsyns were installed in pairs, one turning at a rate of one revolution per revolution of the periscope, and the other turning at thirty-one times this speed. They are referred to as the one speed and the thirty-one speed selsyns, respectively. This arrangement is conventional for aircraft gunsights.

As angle indication is only needed to an accuracy of about $\pm 1°$ on the periscope, it is not necessary to operate the thirty-one speed selsyns.

The thirty-one speed selsyns are mounted, however, for two reasons. The first of these is that they are convenient covers to prevent the entry of dust and dirt into the gearboxes, which would otherwise occur if the selsyns were removed and the openings thus produced not covered. The other reason is that this provides instantly available spare selsyns should one fail.

These selsyns were designed to operate from 115 volts 400 cycles. It would be very inconvenient to operate them from this source, however, since 400 cycle selsyns produce annoying sounds, and, also, 400 cycle equipment is undesirable in that another power source must be maintained for it.

In order to avoid these difficulties, experiments were undertaken to see if these 400 cycle selsyns would work as synchros with 60 cycle power at reduced voltage. Experimentation revealed that they would work well as synchros on 60 cycle power provided that the voltage was held below about 22 volts. With higher voltages, the selsyns heated excessively.

It is true that lower accuracy is obtained with 20 volt 60 cycle power than would be obtained at 115 volts and 400 cycles, but this sacrifice was considered well worth avoiding the nuisance of 400 cycle power.

The one speed selsyns are simply used as synchros to drive dials on the data panel which show the azimuth and elevation.

All power and control circuitry associated with the periscope is brought in through slip rings, so that unlimited rotation of the periscope is possible.

CHAPTER V

DATA ANALYSIS

The film most often used with the periscope camera is Eastman Tri-X, but some work has also been done with Eastman High Speed Infrared. The processing for both these films is identical; the only differences in their use are the facts that focusing controls of the periscope must be set differently for the two films and a Wratten G filter is used with the High Speed Infrared, while no filter is used with the Tri-X. The filter is placed in a standard Eastman slip-on adapter ring, and placed on the camera lens.

Both Tri-X and High Speed Infrared films are developed for 10 to 15 minutes in Eastman D-19 developer at 75° fahrenheit. This represents forced development, and is necessary to obtain optimum results from the periscope.

After the film has been developed and dried, the next step is its analysis. The film is placed on a microfilm reader, and then turned to a place where the camera was stopped a satisfactory length of time to permit the reticle, the clock, and the timing light positions to all be clearly recorded on the film. Most stops during a storm will serve. The reticle is centered on the viewer and then a grease pencil is used to draw the location of the reticle and the one second, one-tenth second, one-hundredth second, and spare (if it is in use) neons on the projection screen of the viewer. Horizontal marks should also be made at the edges of the screen, normally on the one-hundredth second neon line, to show that the film has not been twisted in the viewer gate but is still proceeding through in the same orientation as when the reference marks were recorded.

The next step in the analysis of the film is to proceed to a place where a lightning stroke has been recorded on the film. If this stroke illuminated the central region of the field of view stroboscopically it recorded the reticle pattern on the film at the instant of each flash of illumination.

When these reticle images are located, they should be aligned, one by one, with the reticle pattern which was drawn in grease pencil on the viewer. When a given reticle image is aligned with the reference pattern established with grease pencil, the exact time of the return stroke that recorded the reticle image under consideration may then be read at the reference marks established for each of the timing dots.

In the case of a complex stroke, it is useful to trace the stroke paths in grease pencil on the viewer screen. The film can then be moved and it can be observed whether any of the other paths are of the same form as the ones drawn. This provides a simple and reliable means of detecting multiple discharges over the same paths even in very complex strokes.

After the time has been recorded for each separate discharge, the azimuth and elevation dials should be read on the data panel image both immediately before and immediately after the stroke being analyzed. If they are the same, it is reasonable to assume that the periscope was not moved in this six second period of time, and that this azimuth and elevation for the center of the field apply to the time at which the stroke was recorded. The stroke path, the time of each return stroke, and the direction and orientation of each stroke have now been determined.

If precise measurements of the direction of the stroke are needed, the following information is useful. The angle subtended by the largest of the three concentric circles that make up the reticle is 15°. Therefore, if it is desired to know how far in azimuth some point in the field is from the center of the field, it is only necessary to determine what fraction of one diameter of the large circle the horizontal distance from the center of the field to the point in question is, multiply by 15°, and add (with due regard for sign) this to the azimuth. A parallel procedure may readily be followed for elevation. In this way it is possible to obtain the elevation and azimuth for any point within an angular error of only $\pm$ 1°.

If a sufficiently high film speed is being used, the time of the return strokes may be considered accurate to about $\pm$500 microseconds. A film speed of 600 inches per minute should be sufficient to confer time accuracy of this magnitude. Higher time accuracy is obtainable with higher film speeds, however. It is not certain just what the limiting accuracy of the timing system is, but it may be regarded as better than + 150, and -0 microseconds. This is due to delays in the periscope timing system, especially those associated with the neon bulbs themselves.

Even more accurate timing would be possible at higher film speeds if the time difference between the periscope light flashes and the time marks on the other recording camera were known. This could be determined; one simple way would be to set up an electronic flash unit close to the 150 kilocycle loops. The wires going to the flash tube should be separated rather than run in a two conductor cable, and the open loop of wire should be positioned in such a way that there is appreciable coupling of energy from the capacitor discharge into the 150 kilocycle direction finder channel. A little experimentation would show how much pick-up is needed, and how it should be obtained. The tuned circuit in the 150 kilocycle receivers should be removed for this test, unless the delay it introduces is specifically desired.

Then the cameras could both be started and the periscope trained on the electronic flash unit. This would have to be done at night, of course. The electronic flash unit would then be flashed toward the periscope. This would record the periscope reticle on the film, and also record a disturbance on the 150 kilocycle film record. The cameras could then be shut off, the films developed, and the exact time of the flash on the periscope and the beginning of the disturbance on the 150 kilocycle direction finder measured.

With these times known, the difference between them would simply be the correction which it is necessary to add to the periscope timing to get the time on the rack mounted recording camera.

After this experimental time difference determination has been done, it should be possible to synchronize timing at $\pm$ 15 microseconds or better, if high enough film speeds could be used. A time accuracy of $\pm$ 15 microseconds would probably require film speeds of 10,000 inches per minute and therefore would not be too practical for most observations.

Since the ringing of the 10 kilocycle, and probably the 150 kilocycle, tuned direction finders would be clearly visible at these film speeds, film analysis would present some additional problems. They should not be too difficult to surmount since all one would need to do is take the angle of an individual loop of the 10 kilocycle or 150 kilocycle direction finder modified by a skew factor which the film speed and apparent angle, coupled with knowledge of the frequency of the ringing of the tuned circuit, would provide.

CHAPTER VI

RESULTS

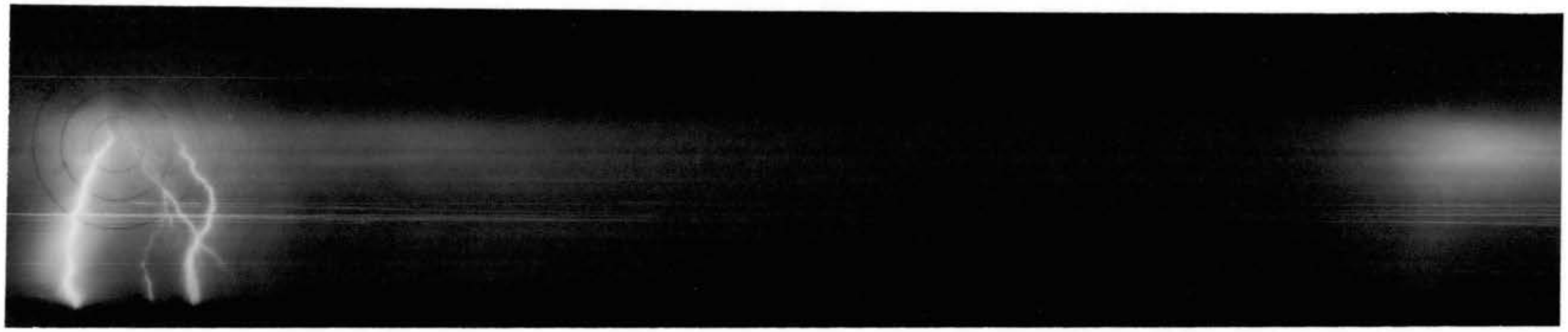
The upper illustration of plate VI is a periscope camera lightning photograph showing several interesting characteristics. It began with two major cloud to ground discharges, close together and occuring simultaniously. These are the left two cloud to ground discharges visible in the plate. Also occurring at that time is another heavy discharge. This one extends from approximately the center of the most strongly recorded reticle pattern downward and to the right, at about a 35° angle from the vertical. It apparently does not reach the ground.

A second discharge occurred over the path of the weaker of the two original cloud to ground strokes about .016 seconds later. In the illustration, it is the third cloud to ground stroke visible from the left. It also recorded the reticle pattern again, although more weakly than it was recorded the first time.

Ramifications, which are ionized streamers extending out into the air from a heavy discharge path, may be seen on the left stroke in plate VI. Ramifications are much more common on the initial discharge of a lightning stroke than on subsequent return strokes.

More or less continuous current flowed through the ionized path of the second return stroke immediately after that discharge. This current continued for about .35 seconds. That this occurred can be seen in the smear of light extending across the photograph. The

PLATE VI LIGHTNING PHOTOGRAPHS BY THE PERISCOPE



current through this channel varied during that time, however. A careful examination will show a pattern, identical in form to the ionized path through which the current is flowing, recorded at several places in the smear of light extending to the right. One of the more readily apparent of these patterns occurs only a short time after the return stroke itself. This one occurred as a result of a sudden reduction, followed by an increase, in the current through the path. The result of this was a decrease in luminosity for a few milliseconds. This was recorded as a dark line, having the same form as the return stroke. At the far right can be seen two more faint brightenings of this return stroke. These are apparently associated with more lightning activity back in the clouds, since the clouds are strongly luminous at this time.

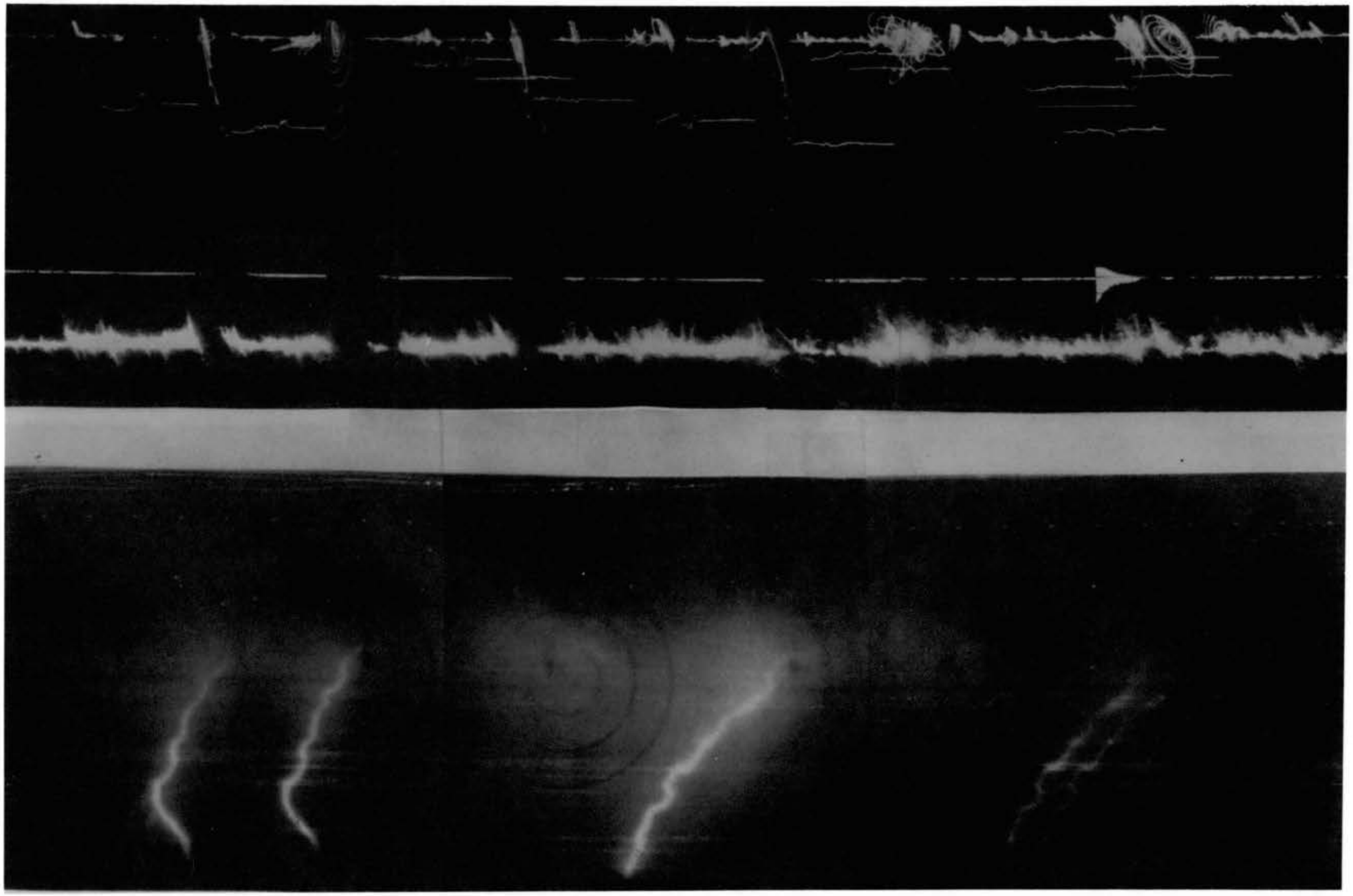
The lower photograph of plate VI is also a very interesting lightning stroke. It features two heavy cloud to ground discharges occurring at the same time, then about .08 seconds later there is some invisible activity in the clouds. This is followed by a multiple return stroke intracloud discharge which has a vertical path length comparable to that of many of the longer cloud to ground strokes. On the basis of meteorological data, chiefly an assumed lifting condensation level of 5,000 feet, the mean altitude of this intracloud discharge is about 12,000 feet and the visible part of it is some 7,000 feet long.

It is unlikely that this discharge might extend on to the ground behind clouds. The reasoning that leads to this conclusion is simple. It is not likely that these intracloud discharges are significantly further away than the cloud to ground discharges occurring a fraction of a second before. If they were, the cloud to ground discharges would be occurring between the atmospherics laboratory and the cloud. This is untenable, since the upper part of the cloud to ground strokes are not seen to terminate in dendritic branching, as they must if they are discharging a space charge. Their upper ends must therefore have been hidden by clouds. If, then, the intracloud discharge is not further from the atmospherics laboratory than the cloud to ground discharges, there are no clouds in a position to hide a section of the intracloud discharge extending on to the ground, or they would also have hidden the cloud to ground strokes.

Plate VII shows a periscope camera photograph of a cloud to ground lightning stroke, together with the electromagnetic recordings from the rack mounted camera for the same lightning stroke. The first two return strokes are .028 seconds apart, and they are over the same path. Then .092 seconds later another return stroke, apparently somewhat closer, occurred. This return stroke involved a very heavy flow of current as may be seen by its intense luminosity. It was followed in .034 seconds by some invisible intracloud activity. Next, .080 seconds after the last cloud to ground discharge, another weak return stroke occurred along the same path. There is also a horizontal path visible at the top and to the left of this return stroke. Another similar return stroke occurs only about .007 seconds later.

The electromagnetic impulses recorded for each lightning stroke may be clearly seen in the upper section of plate VII. The uppermost trace is the ten kilocycle instantaneous direction finder. The waveforms below it are triggered waveforms from the broadband channel. The triggering of the waveforms is controlled by luminosity from the lightning strokes, so that the waveforms do not necessarily occur at the time of

PLATE VII PERISCOPE PHOTOGRAPH AND ELECTROMAGNETIC RECORDINGS



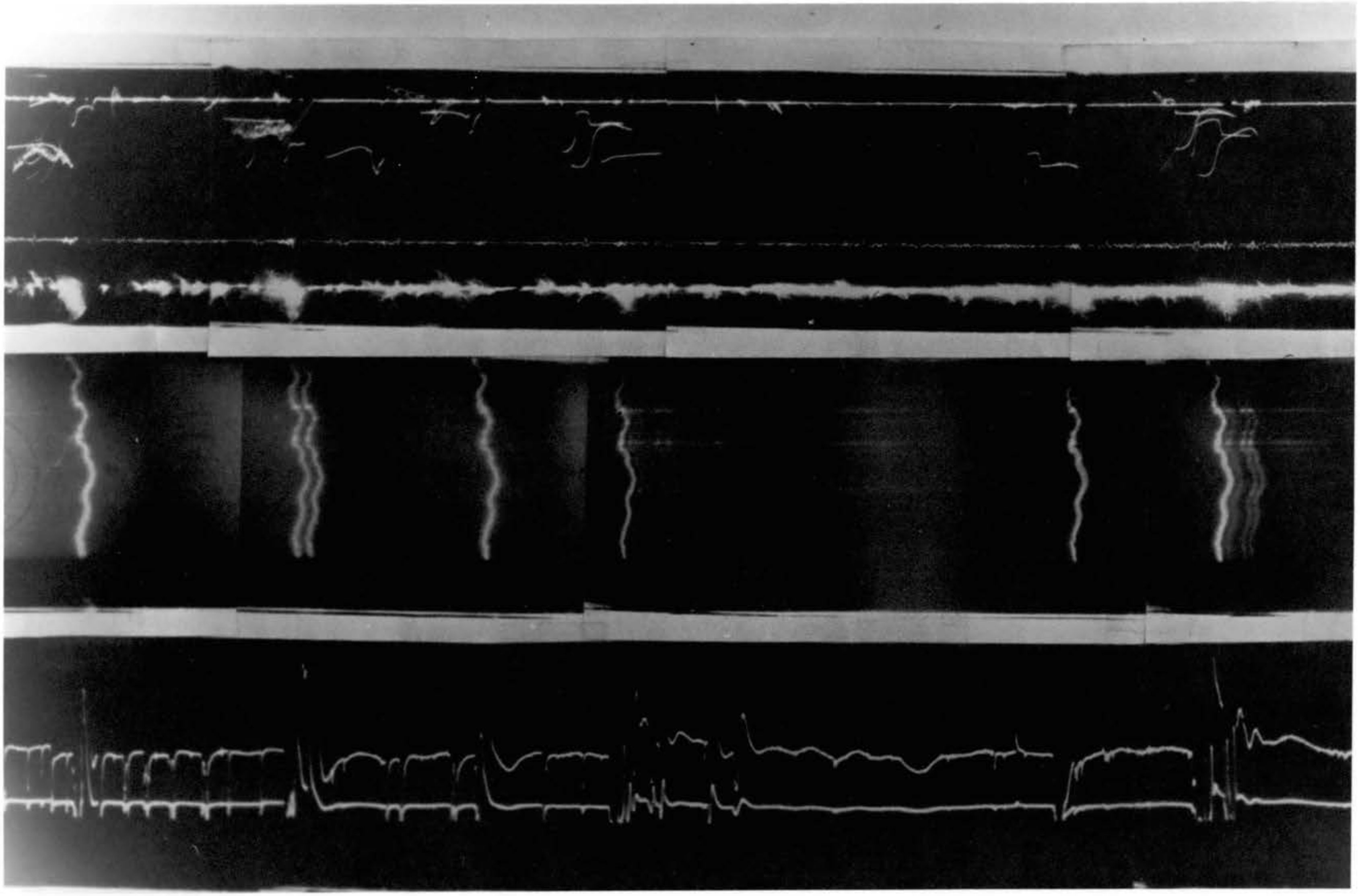
the greatest electromagnetic activity. The second trace from the bottom is timing. The lower trace is the 150 kilocycle instantaneous direction finder.

The electromagnetic recordings and the lightning stroke photographs are placed in approximate time synchronism in the photograph, so that it is possible to look vertically upward from a lightning return stroke to find the electromagnetic recording produced at the time of that discharge.

It can be seen that there is a significant amount of electromagnetic activity occurring in the time between the photographed lightning return strokes. Part of this is due to more distant electrical activity which cannot be photographed from our location. Part of it is from the opposite direction, and is therefore not photographed. Still more of it represents discharges which were either concealed by clouds or not sufficiently luminous to be recorded in the photographs, but were connected with the lightning stroke that was photographed.

Plate VIII also shows a lightning stroke together with its electromagnetic recordings. The first return stroke, at the far left, shows ramifications very clearly. It is followed, after a normal delay, by two other return strokes very close together. There is another return stroke, then another. The last mentioned shows current persisting in the channel for a very significant amount of time after the actual discharge. The two bright spots in the channel, which left the longest and most readily visible smears, are places where the channel proceeds directly toward or away from the observer for a significant length of path. This simply means that there is a greater amount of luminous flux proceeding from the direction of those spots because there is a larger volume of ionized air there. These points in the path are also readily discernible

PLATE VIII PERISCOPE PHOTOGRAPH AND ELECTROMAGNETIC RECORDINGS



in the last return stroke and its afterglow. The glow following the last return stroke shows several sharp pulses of current.

Lightning having these more brilliantly glowing sections of path has often been seen by observers. Because the more brilliantly glowing sections can be clearly seen if current persists a sufficiently long time in the channel after the final return stroke, such lightning is often referred to as "bead lightning". A lightning stroke occurs, then the observer sees several brightly glowing beads along the path where the discharge just occurred. This has long been regarded a result of current flowing for a considerable length of time through the path in combination with a path shaped so that it proceeds directly away from or toward the observer for some significant length. Plate VIII may be taken as strong supporting evidence for this theory. It is, to the author's knowledge, the only moving image photograph of bead lightning.

The electromagnetic recording presented at the top of plate VIII corresponds to the one in plate VII. The traces have the same significance, and it too is positioned so that one need only go vertically from the lightning stroke up onto the electromagnetic recording to determine what electromagnetic effects correspond to a given return stroke. Here again, electromagnetic effects are not confined to the times of visible strokes.

The lower film record shown in plate VIII is a continuous recording of the time derivative of the vertical component of the electric field. The two traces visible on this film represent the same parameter recorded at two different gains. The gain of the upper trace is ten times that of the lower one. This recording rather than the one above the periscope camera film, because it is continuous in time, permits the most ready interpretation of what occurred.

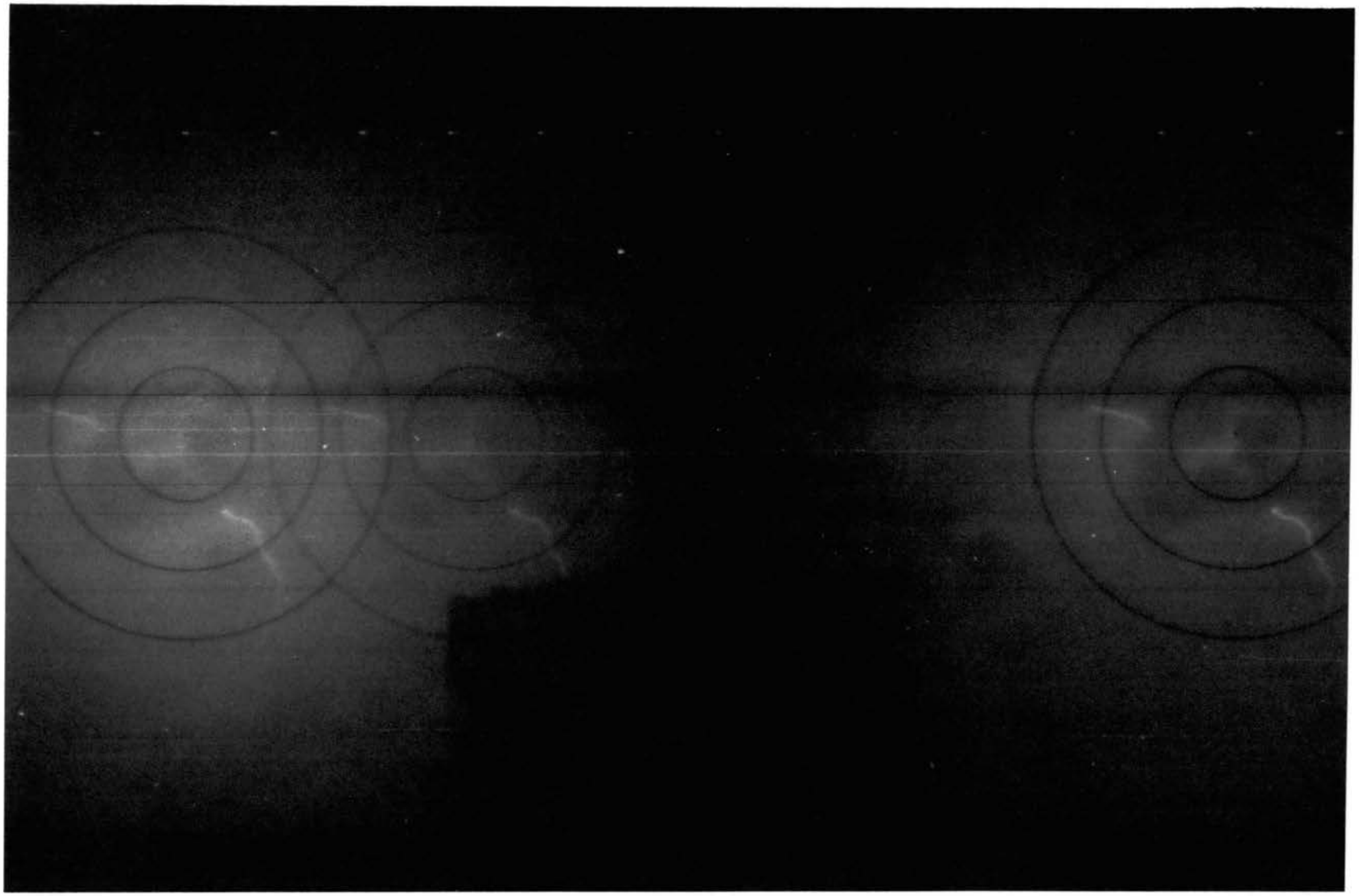
Very strong disturbances are visible on this recording at the time of each return stroke. Other weaker disturbances are visible during the time between strokes. It is significant to observe that most of the disturbances occurring between return strokes are of opposite polarity to those occurring at the time of the return strokes. The polarity observed for the changes occurring at return strokes is the polarity one would expect from the usual concept of positive charge being transported upward by a cloud to ground lightning stroke. The disturbances occurring between return strokes, however, appear to represent a motion of charge in the opposite direction. Why this should be and how it is consistent with the recurrence of another return stroke also transporting positive charge upward is not at all obvious.

It is interesting to observe the lower electromagnetic recording immediately after the last return stroke. Here a general rise in the high sensitivity (upper) beam shows the more or less continuous flow of current which occurs after this return stroke. A similar effect may also be noted for the other return stroke which shows significant afterglow. It is the fifth from the left.

Plate IX shows a dramatic intracloud discharge. The path can be seen at two places; it is obscured by cloud in the center. It is visible where it intersects the second ring of the reticle at two points. One of these is at the left and one is at the lower right.

This discharge was luminous for a length of time which was not short compared to the time necessary for the film to move the width of its image. As a result, it was blurred slightly by film motion. The third return

PLATE IX INTRACLOUD LIGHTNING



stroke at the far right was faster than the other two. It can be seen to be sharper.

It is significant to examine closely the images of the reticle recorded by the first two return strokes. These images are much sharper at the top and the bottom than they are at the right and left. This is a logical result of film motion during the time the reticle was illuminated. The period of significant luminosity from this stroke was on the order of 500 microseconds for the first return stroke, and a millisecond for the second return stroke. These times are derived from the width in the direction of film motion of the blurr of the reticle.

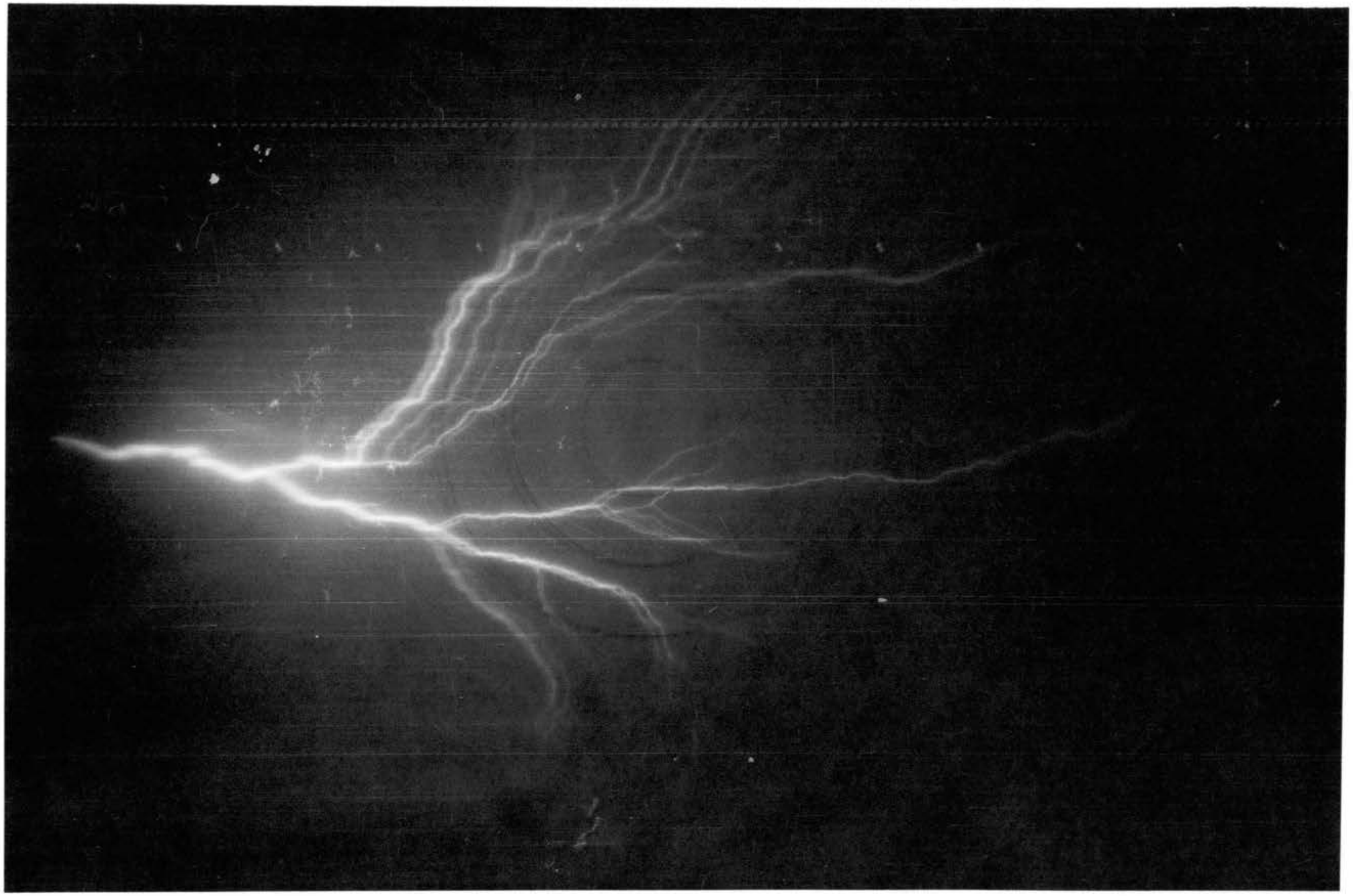
The dots extending horizontally across the top of the photograph slightly over $\frac{1}{2}$ inch apart are timing marks; the time elapsing between two of them is 1/100 second.

The angular object visible immediately below the second reticle pattern and again about two inches to the right is a corner of the van used to house the atmospherics laboratory weather radar. It was recorded stroboscopically by the first and second return strokes.

Plate X is a highly dramatic lightning stroke, photographed by the periscope camera at a lower film speed and a higher elevation than the previously presented results. The elevation represented by the center of the reticle in plate X is about 47° above the horizon.

The most exceptional feature of this lightning stroke is the dendriform branching shown of the stroke channels. This indicates that the space charge which this lightning stroke was discharging was actually located in the region shown in plate X. That is, this is a photograph of a space charge region as it is discharged. The main stroke channel extends out of the field to the left.

PLATE X PERISCOPE PHOTOGRAPH OF LIGHTNING ALMOST OVERHEAD



Two distinct images of the reticle can be seen recorded on the film. The left one of these was recorded by the first (left) discharge and the right one was recorded by the second discharge, which was the strongest. The paths of these two discharges can be seen separated horizontally by about .1 inches. This separation corresponds to about .012 seconds.

Five separate discharges can be seen along one of the paths with some modification of the path taking place between the second and third of these. The path here referred to is the heavy one at the upper left of the central region of the photograph. It almost coincides with the outer circle of the reticle at about the ten o'clock position.

Also interesting are the two paths extending far to the right, finally disappearing behind clouds.

A rough estimate, based on the assumption of a cloud base height of 5,000 feet, of the size of the area shown in this photograph is about 6,000 feet in the vertical direction and 6,000 feet at its center in the horizontal. The stroke, as seen in plate X, is distorted somewhat since the periscope was looking at it from an angle if we assume that the stroke was relatively flat and parallel to the base of the cloud. This is why the proportions of the dimensions presented do not match the proportions of the photograph.

The row of dots about half an inch below the top of the photograph is the one-hundredth second timing marks and the row of much more widely spaced dots below them is the tenth second timing marks.

For all the pictures presented in this chapter, the absolute time is known for each discharge shown, and the angular orientation with respect to the atmospherics laboratory of each point on each discharge is known to an accuracy of $\pm 1°$ in both azimuth and elevation.

It is readily possible to identify details on electromagnetic recordings as having been coincident with a given discharge, and to point out corresponding features in the lightning photographs and the electromagnetic recordings. The periscope camera is clearly a powerful new tool to aid in unlocking the secrets of lightning.

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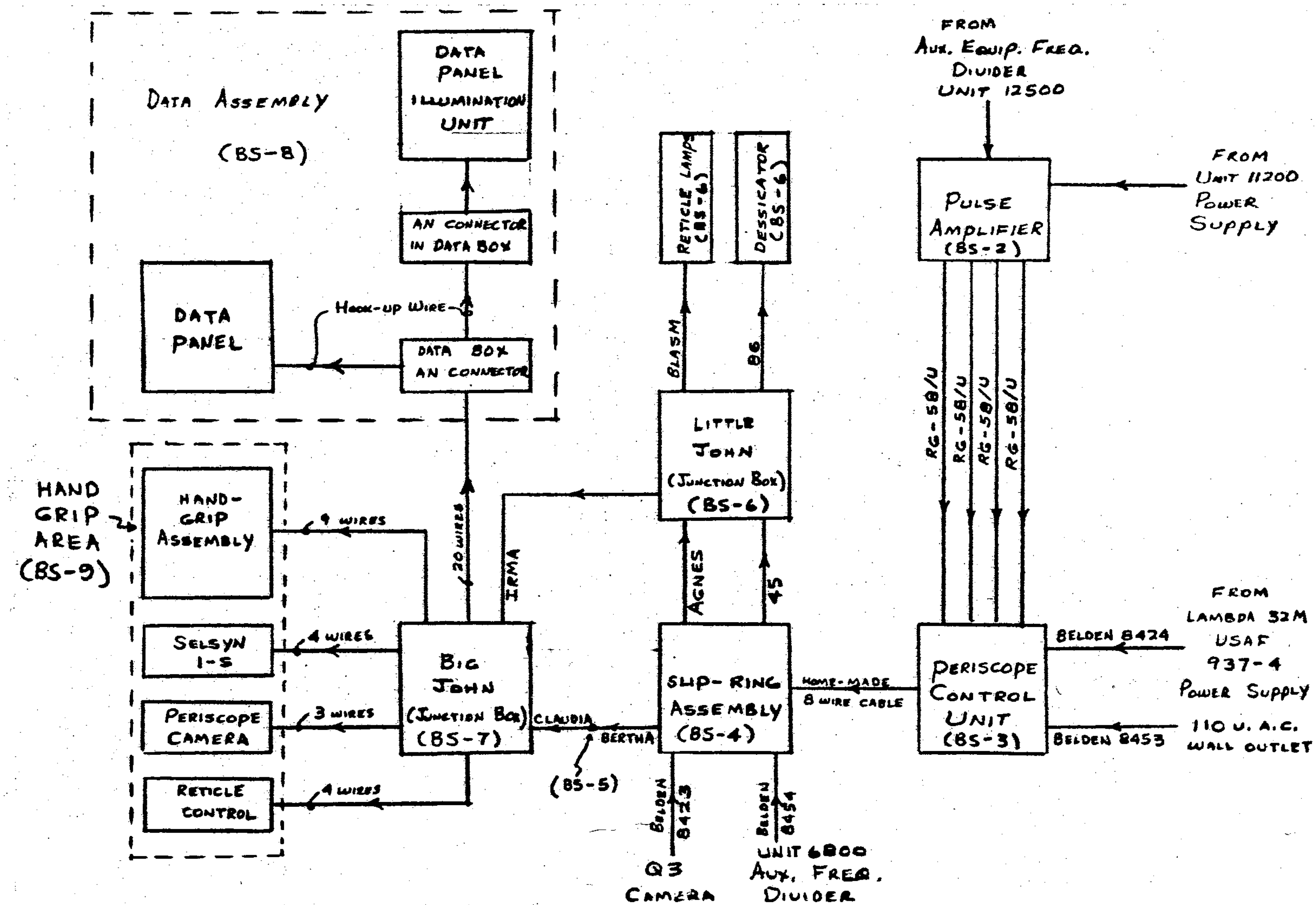
APPENDIX

ELECTRICAL WIRING DIAGRAMS OF THE PERISCOPE AND ASSOCIATED ELECTRONIC UNITS

Periscope
Block Diagram

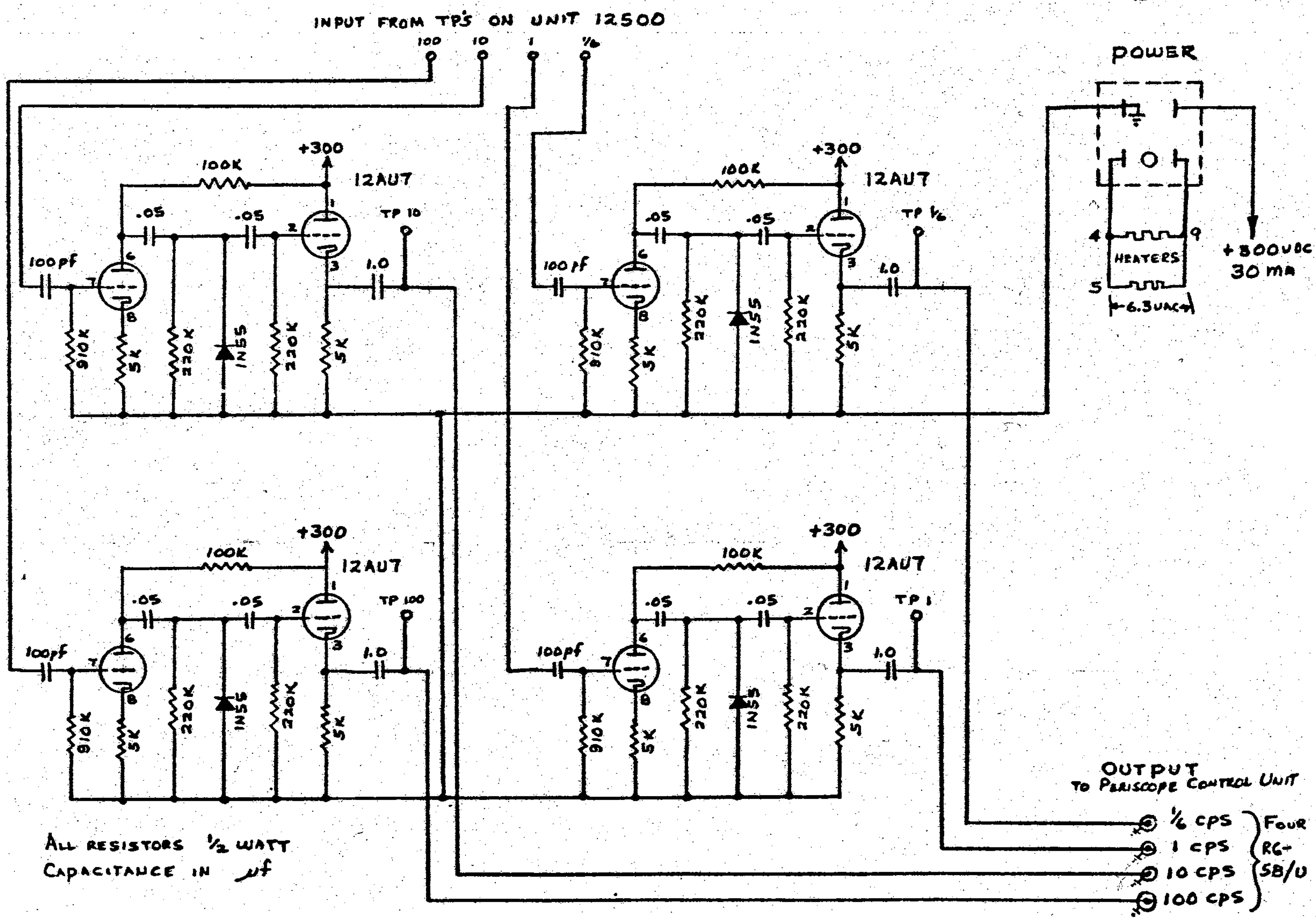
BS-1



99

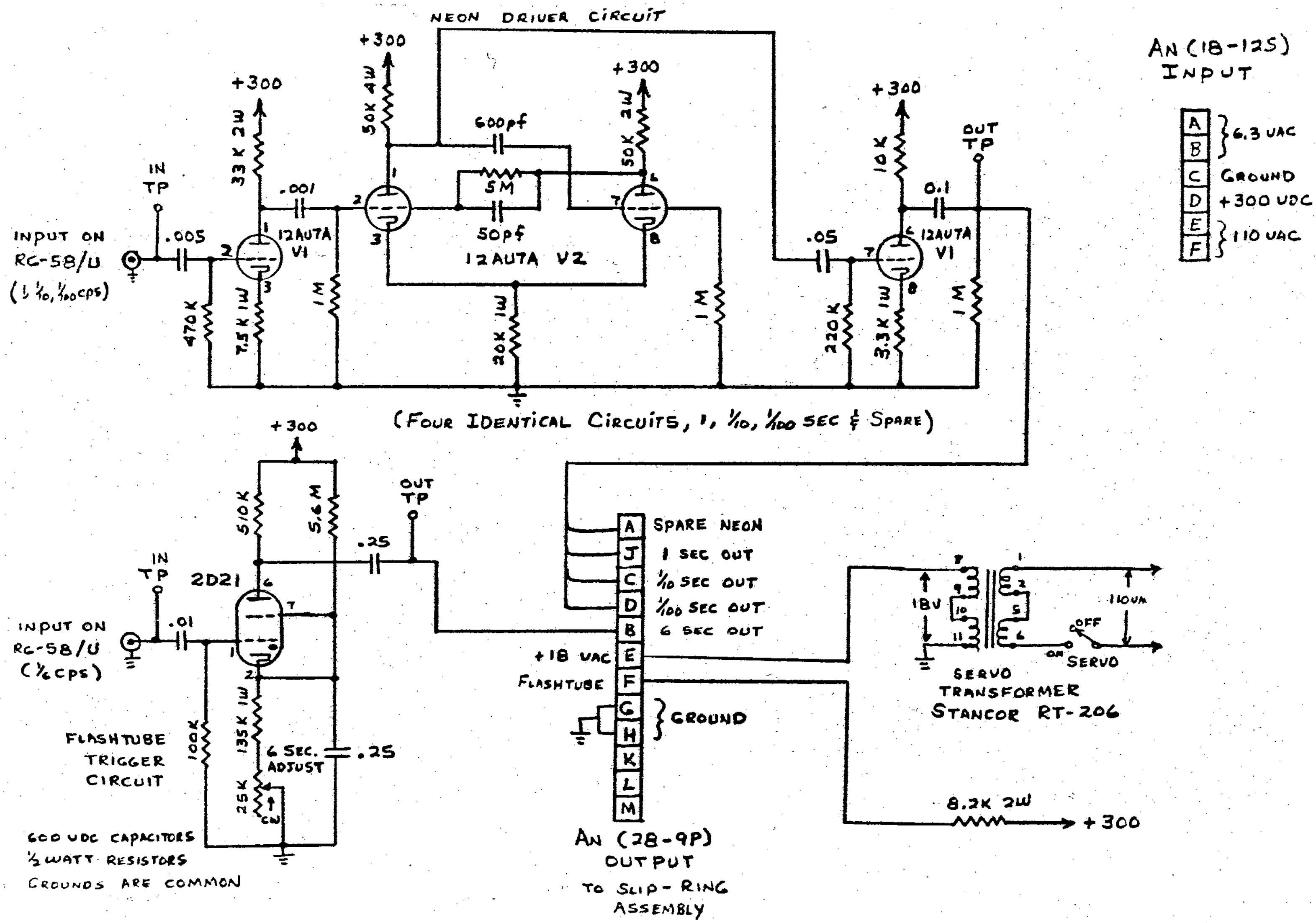
Pulse Amplifier

BS-2



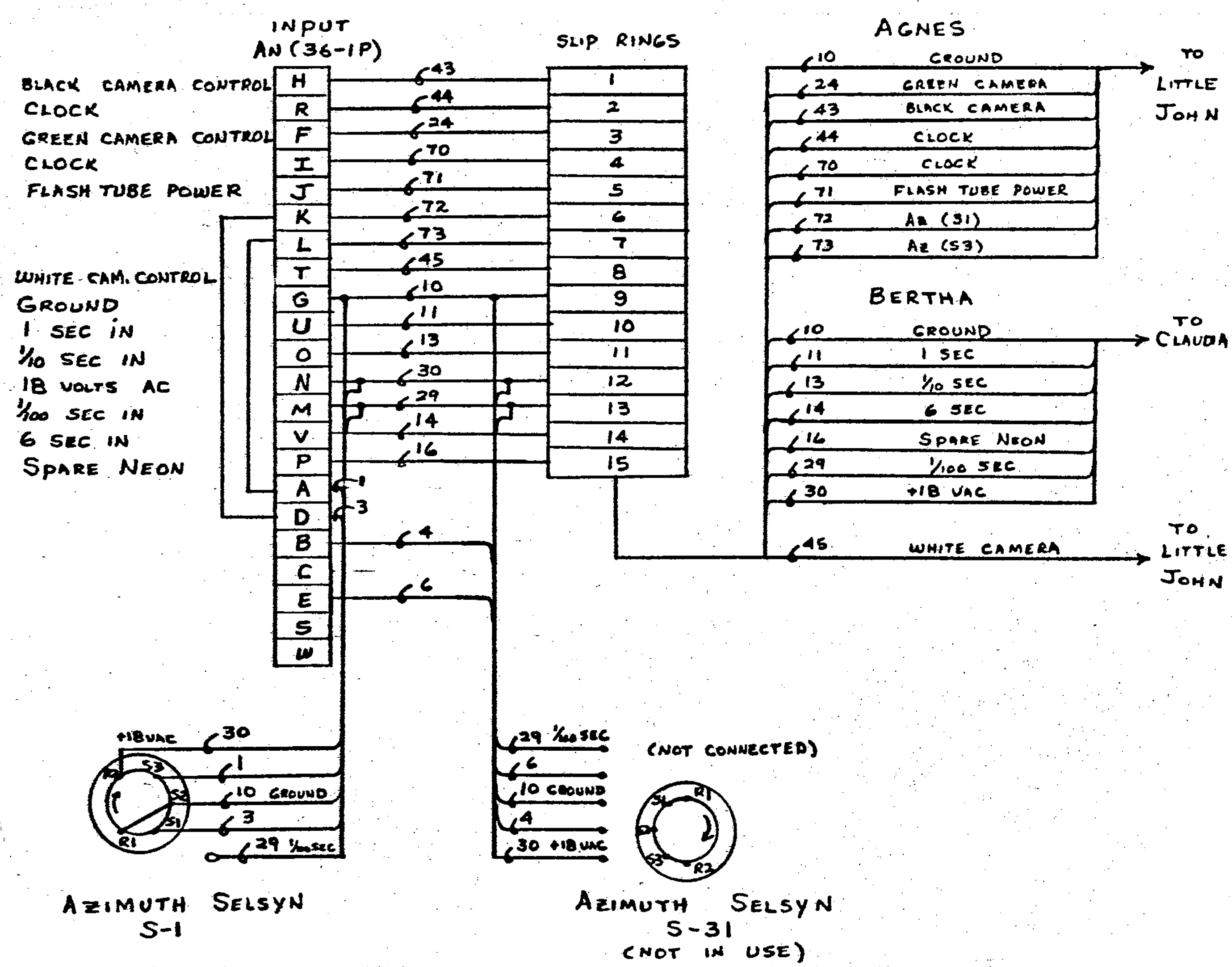
Periscope Control Unit

BS-3



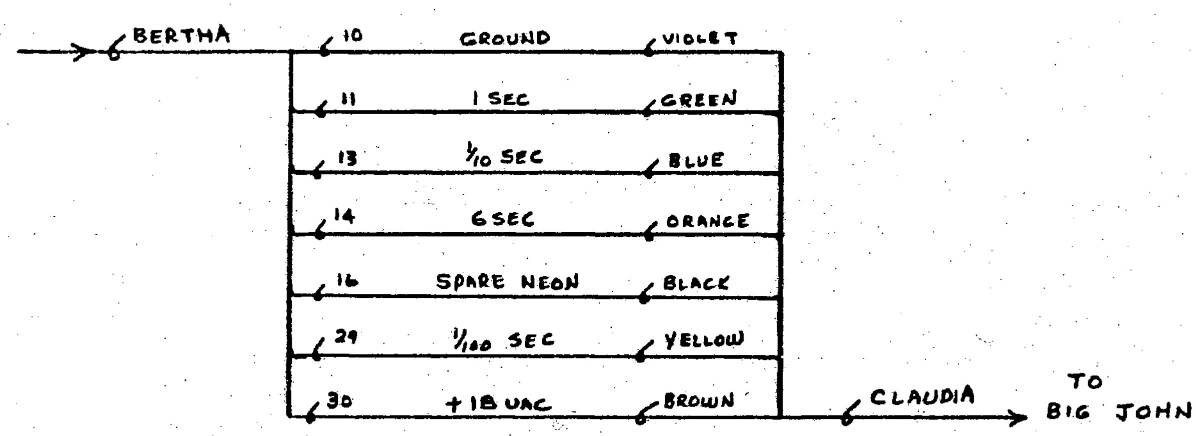
Slip-Ring Assembly

BS- 4



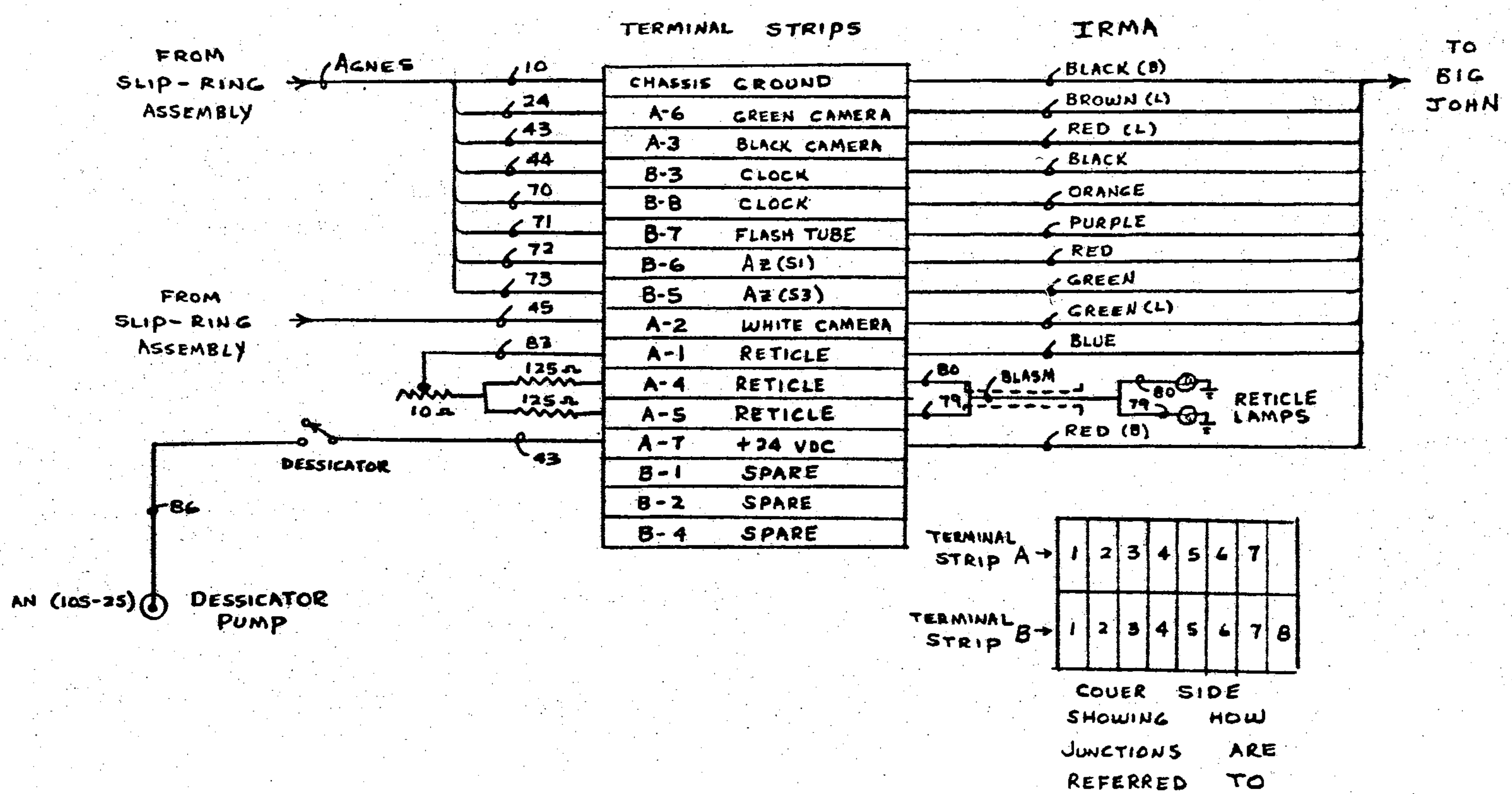
BERTHA- CLAUDIA SPLICE

BS-5

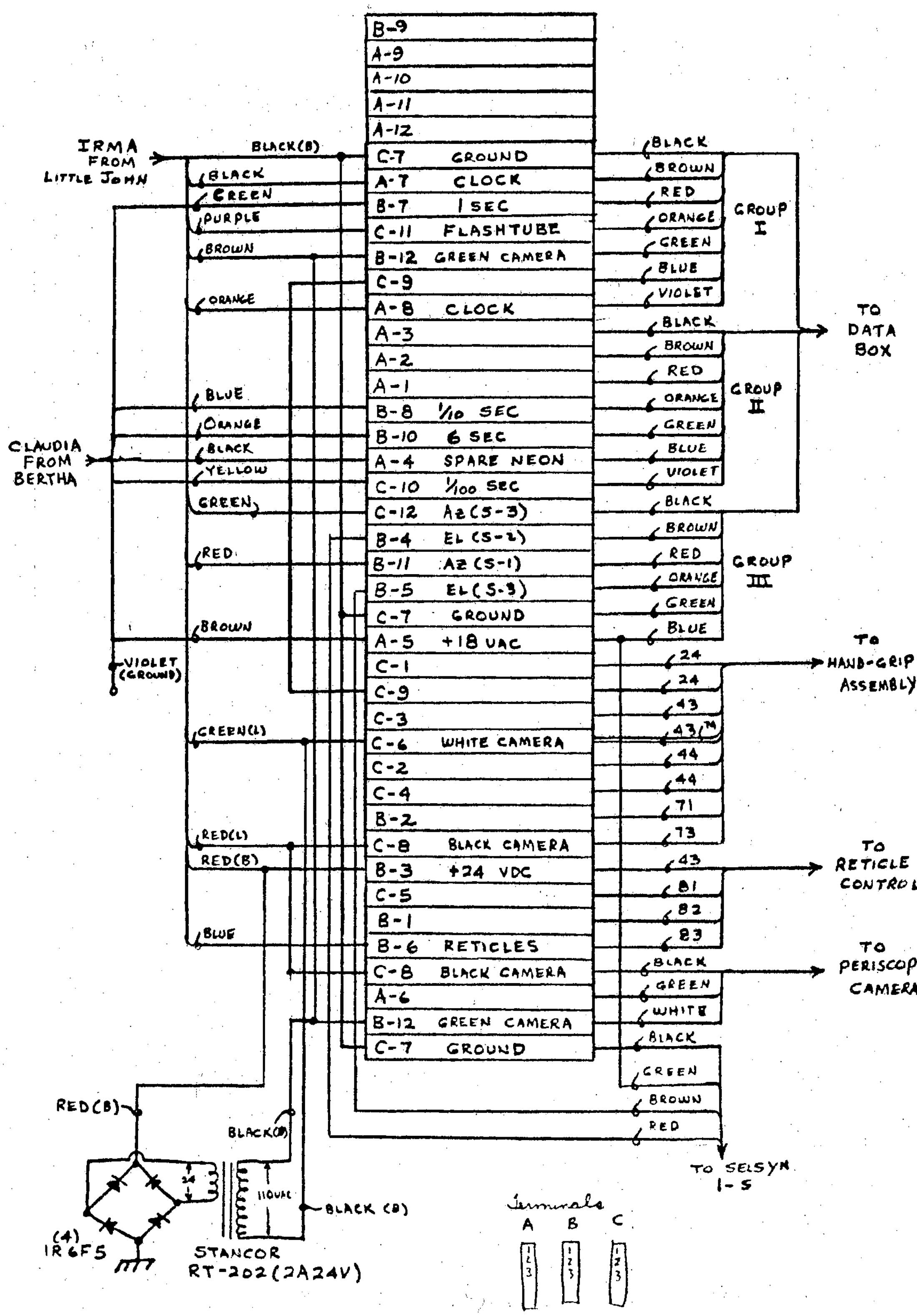


LITTLE JOHN
(SMALL JUNCTION BOX)

BS-6



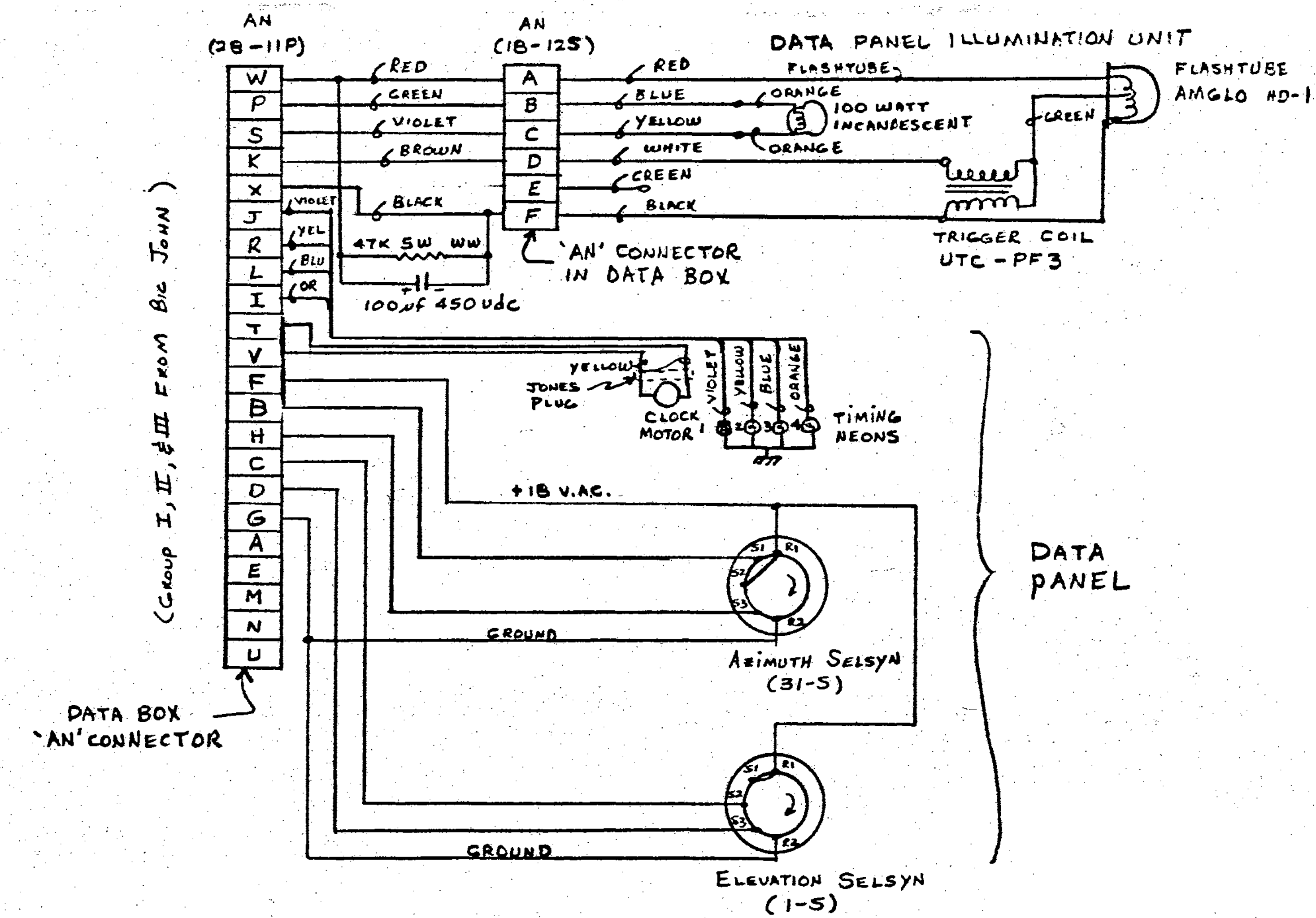
BIG JOHN (LARGE JUNCTION BOX)



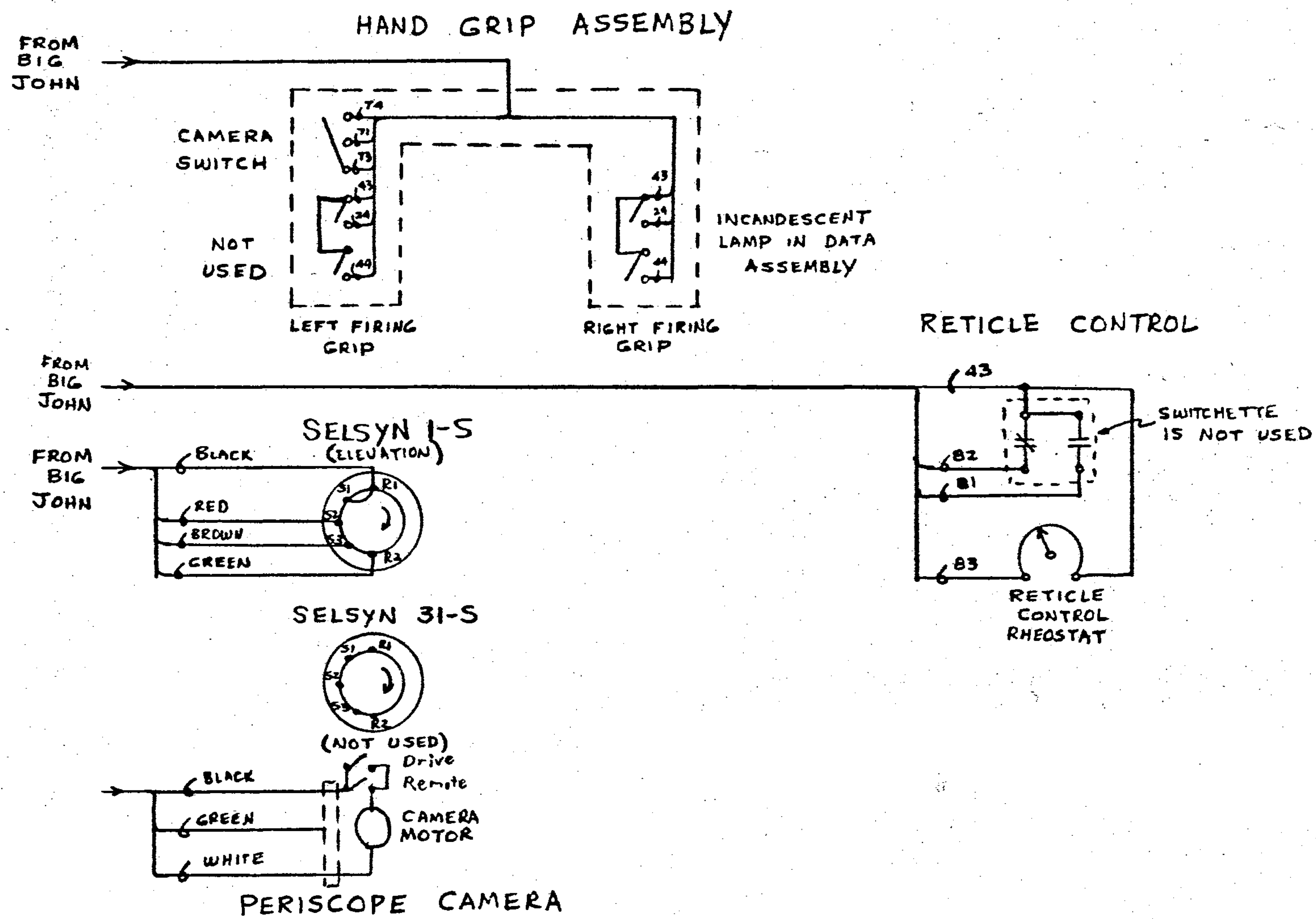
BS-7

Data Assembly

BS-8



HAND-GRIP AREA



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