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THE POLARIZATION OF ZODIACAL LIGHT

By

Maynard Cowan, Jr.

A Thesis

In partial fulfillment of the

Requirements for the Degree of

Master of Science in Physics

University of New Mexico
1951

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E F Castetter

DEAN

February 10, 1951

DATE

THE POLARIZATION OF ZODIACAL LIGHT

by

Maynard Cowan, Jr.

Thesis committee

Victor H. Regener

CHAIRMAN

John R. Green

John G. Breiland

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ACKNOWLEDGMENTS

Counsel and guidance were gratefully accepted from Professor V. H. Regener throughout the project. Thanks are due Allan F. Beck and James D. Lindsay without whose assistance this work could not have been done. The theoretical advice given by Dr. Roy Thomas was also appreciated.

162355

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Introduction. Previous investigations have shown that the illumination of the night sky is composed of light from several sources. The zodiacal light is an important one of these light sources. On clear moonless nights the zodiacal light is seen as a faint pyramid of reddish yellow to white light in the evening western sky or morning eastern sky. It is best observed in the lower or middle lattitudes. The axis of the light pyramid varies only slightly from the ecliptic. [1]

Statement of the Problem. It was the purpose of this study, (1) to measure the polarization of zodiacal light, (2) to investigate the orientation of the plane of polarization, and (3) to deduce from results obtained information concerning the origin of zodiacal light.

It is almost certain that zodiacal light is solar radiation which is either reflected or scattered from a lens shaped cloud of particles. Two views, however, are held as to the location of this cloud, namely the planetary

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1 S. K. Mitra The Upper Atmosphere (Calcutta: The Royal Asiatic Society of Bengal, 1948) Page 454

theory in which the sun is at the center and the atmospheric theory in which the earth is at the center.

With the sun at the center of the cloud as assumed by the planetary theory, the particles must be very large compared to molecular dimension, or they would be ultimately drawn into the sun by the Poynting-Robertson Effect. The following is a qualitative discussion of the theory of this effect:[2]

> Radiant energy possesses mass and momentum. Since the small body loses as much heat-energy into space as it gains from the sun, there is no net change in its mass. The outgoing radiation, however, carries away not only mass but a proportional fraction of the momentum of the moving body, while the momentum of the incident solar radiation is directed straight away from the sun and produces radiation pressure, but does not contribute any angular momentum about the sun. The orbital angular momentum of the body therefore steadily diminishes, and the semi-parameter of the orbit along with it.

If such large particles make up the zodiacal cloud, then the polarization observed in the zodiacal light would have to occur during the reflection process on these particles. Since the particles must certainly be oriented in space in a completely random manner, one would expect at most only a very small percentage of polarization.

---

2 H. N. Russell, R. S. Dugan, and J. Q. Stewart <u>Astronomy</u> (Boston: Ginn and Company, 1945) page 360

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2 H. N. Russell, R. S. Dugan, and J. Q. Stewart Astronomy (Boston: Ginn and Company, 1945) page 550

If the earth is at the center of the cloud, as is assumed in the atmospheric theory, the particles need not be large. Hulburt[3] and Vegard[4] assumed the outer region of the atmosphere to be the scattering cloud and the particles to be molecules. If the size of the scattering particles is comparable to the size of molecules, one would expect the scattered light to exhibit an intensity distribution given by Rayleigh's law. A considerable amount of polarization would be expected with the maximum percentage of polarization occurring when the angle at the scattering particle between the line of propagation of the irradient light and the line of viewing is ninety degrees.

Summary of Previous Work. Duffay[5] made measurements of the polarization of the night sky light with special reference to the region of the zodiacal pyramid. He has made a graph of his readings showing the percentage of polarization as a function of angular distance from the sun. One curve on the graph was drawn for the night sky light from the zodiacal cone, another for the night sky

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3 E. O. Hulburt, Phys. Rev., 35, (1930) page 1098

4 S. K. Mitra, compiler, The Upper Atmosphere (Calcutta; The Royal Asiatic Society of Bengal, 1948) page 463

5 Ibid., page 489

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5 __Ibid.__, page 489

light in the darker regions of the sky. The graph showed that the night sky light in the region of the zodiacal pyramid was always more strongly polarized than the night sky light from other regions of the sky. The difference was found to become even more pronounced as the angular distance from the sun decreased. For example, one of the curves on the graph showed that lightt from the region of the zodiacal cone was three per cent polarized when the sun was an angular distance of ninety degrees from the point observed and twenty per cent polarized when the angular distance from the point observed to the sun was fifty degrees. Light from regions far removed from the zodiacal cone was shown by the other curve of the same graph to be only two per cent and three per cent polarized respectively for these same angular distances. The plane of polarization of the night sky light was found to pass consistently through the sun regardless of the position off the investigated region.

As a result of Dufay's work itt is generally concluded that the zodiacal light is the only polarized component of the night sky light.

Although Dufay measured the polarization of the light from the zodiacal pyramid, it should be pointed out that he apparently did not measure the polarization of zodiacal light. To measure the percentage of polarization of zodiacal light

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alone one would have to have some method of determining what part of a given light intensity was due to zodiacal light and what part was due to the other sources of the night sky light. In other words the background light intensity, that intensity due to the night light which is not zodiacal light, would have to be determined. In this thesis a method of determining background light intensity and hence the polarization of zodiacal light will be presented.

CHAPTER II

DESCRIPTION OF APPARATUS

For details of the apparatus not described in this thesis reference is made to the work of Allan F. Beck[6] and James D. Lindsay[7].

Description of Telescope. A war-surplus General Electric anti-aircraft searchlight was modified for use as a telescope in this work. The carbon arc was removed and its mounting was converted for use as the photomultiplier tube mounting. The glass covering and its supports as well as all other unnecessary parts were removed from the searchlight.

Mounting of Telescope. The telescope was given an equatorial mounting. See Figure One. The azimuth and elevation controls of the searchlight then became the hour angle and declination controls of the telescope. The removal of some of the parts and the equatorial mounting

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6 Allan F. Beck, "The Intensity of Zodiacal Light" (unpublished Master's thesis, The University of New Mexico, Albuquerque, 1951)

7 James D. Lindsay, "A New Automatic Recording Method for Measuring the Shape and Position of Zodiacal Light" (unpublished Master's thesis, The University of New Mexico, Albuquerque, 1951)

CHAPTER III

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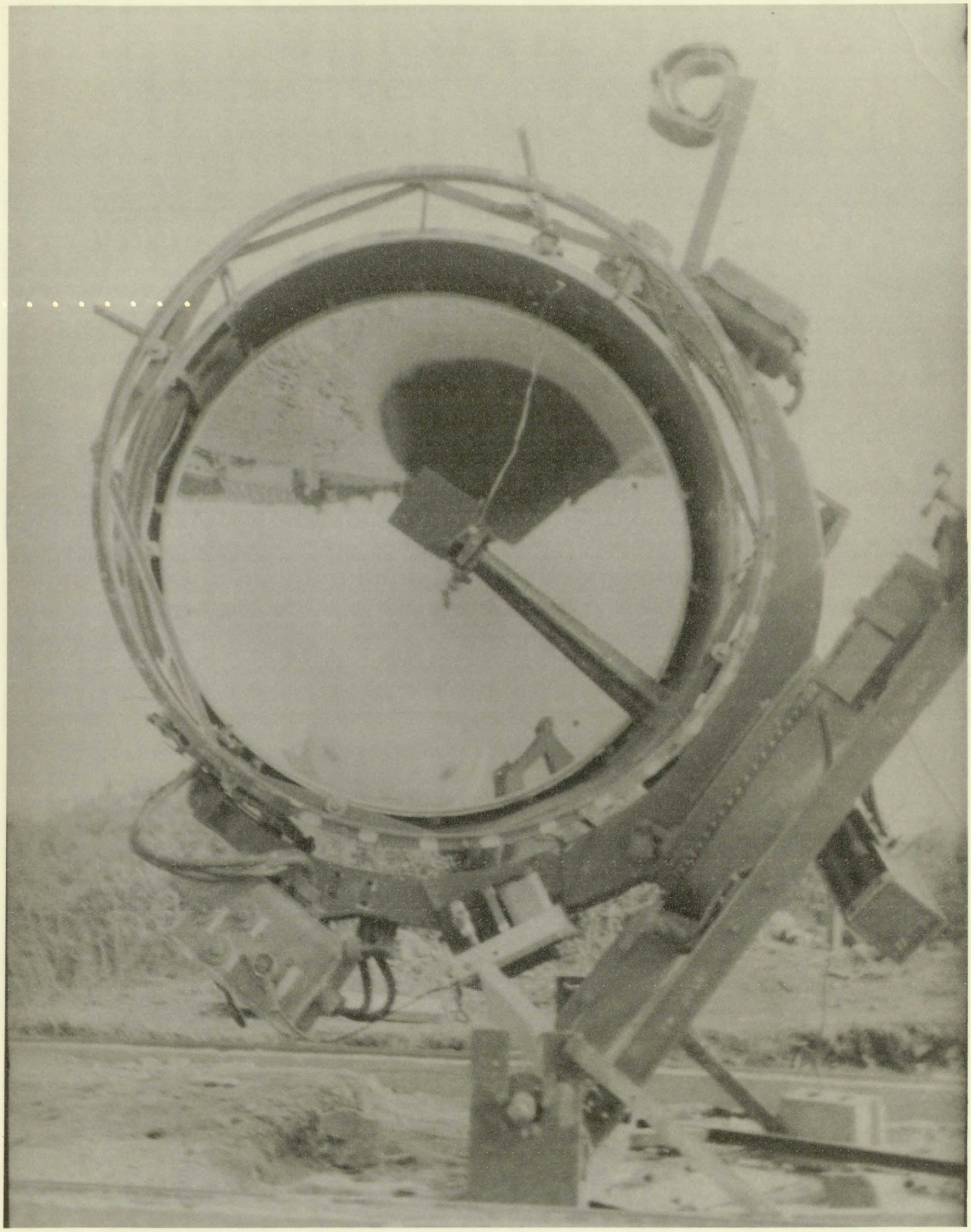
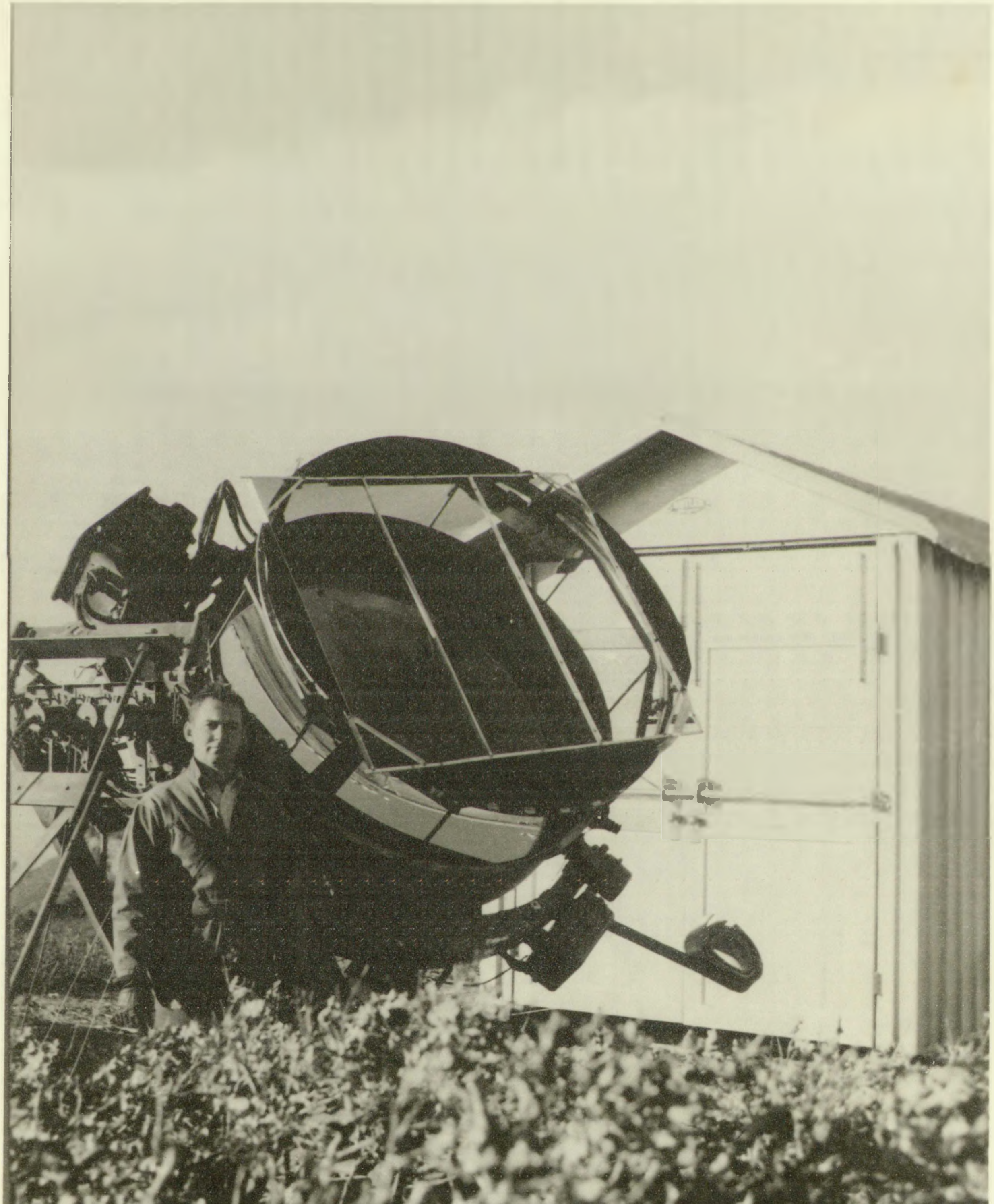


TELESCOPE WITHOUT POLAROID

FIGURE 1



TELESCOPE WITH POLAROID

FIGURE 2

made it necessarry to re-balance the telescope.

Power four Operation of the Telescope. The powr or the remotely comttrolled motion of the telescope was uished by six twelve-voolt batteries and a gasoline powered errator. The generator waas used as the source of 110 volts a.. nd in addition the generator motor was used to turn an i:ty-volt d.c. generattor which was used to charge the bateies.

Automatiic Remote Control. When the telescopewa oper-ated by the auttomatic control it turned in the direcic of increasing hour angle starting from south until 180 e-grees later the declination automatically increased hie degrees and the hour angle sweep was repeated. The .owst declination possiible was minus fifteen degrees and te highest, seventyy--two degrees. After completing 360 eees of hour angle att the seventy two degree declination,tl declination auttomatically returned to minus fifteen eees to start a new sweep of the sky.[8]

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8 James ID.. Lindsay, "A New Automatic Recordin thod for Measuring thee Shape and Position of Zodiacal Ligt" (unpublished Masster's thesis, The University of New Mexco, Albuquerque, 19951)

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<u>Power for Operation of the Telescope</u>. The power for the remotely controlled motion of the telescope was furnished by six twelve-volt batteries and a gasoline powered generator. The generator was used as the source of 110 volts a.c. and in addition the generator motor was used to turn a ninety-volt d.c. generator which was used to charge the batteries.

<u>Automatic Remote Control</u>. When the telescope was operated by the automatic control it turned in the direction of increasing hour angle starting from south until 180 degrees later the declination automatically increased three degrees and the hour angle sweep was repeated. The lowest declination possible was minus fifteen degrees and the highest, seventy-two degrees. After completing 180 degrees of hour angle at the seventy two degree declination, the declination automatically returned to minus fifteen degrees to start a new sweep of the sky.[8]

<u>Manual Remote Control</u>. When the telescope was operated by the manual control the hour angle and declination of the telescope would correspond to the dial readings on

---

8 James D. Lindsay, "A New Automatic Recording Method for Measuring the Shape and Position of Zodiacal Light" (unpublished Master's Thesis, The University of New Mexico, Albuquerque, 1951)

the manual control panel. See Figure Four.

Explanation of the Block Diagram. The block diagram of the electronic equipment is shown in Figure Three. The units set off by the dotted lines were mounted on the telescope. All other units with the exception of the voltage regulator were mounted in two metal cabinets as shown in Figures Four and Five. The photomultiplier tube which was mounted at the focus of the mirror received the light that the mirror had gathered and changed it into an electric signal which varied with the intensity of the light. This signal was amplified by a desired amount and the resulting signal was read on the meter labeled Signal Voltage, shown in Figure Four. The reading of this meter was thus a measure of the intensity of light received by the telescope.

The signal was inverted by the voltage inverter and passed to the discriminator. The discriminator changed a continuously varying signal into a signal that varied by steps. This signal was then passed to the number one grid of the cathode-ray tube. The intensity of the luminous spot on the cathode-ray tube was therefore made to vary in steps as the light received by the telescope varied continuously. The horizontal driver was connected to the automatic control of the searchlight so that the spot on the cathode-ray tube would move from right to left as the searchlight turned from

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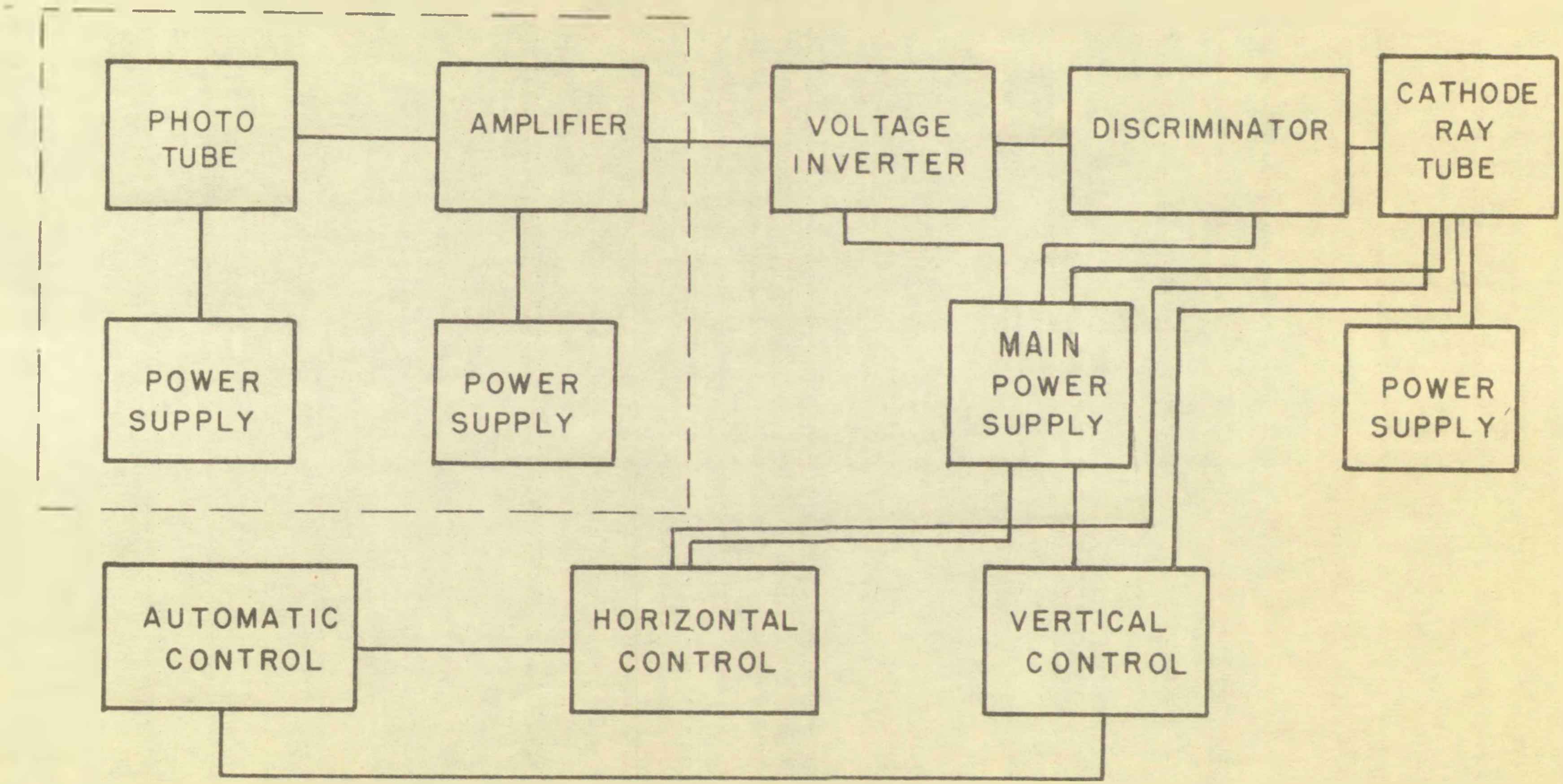

BLOCK DIAGRAM

FIG. 3

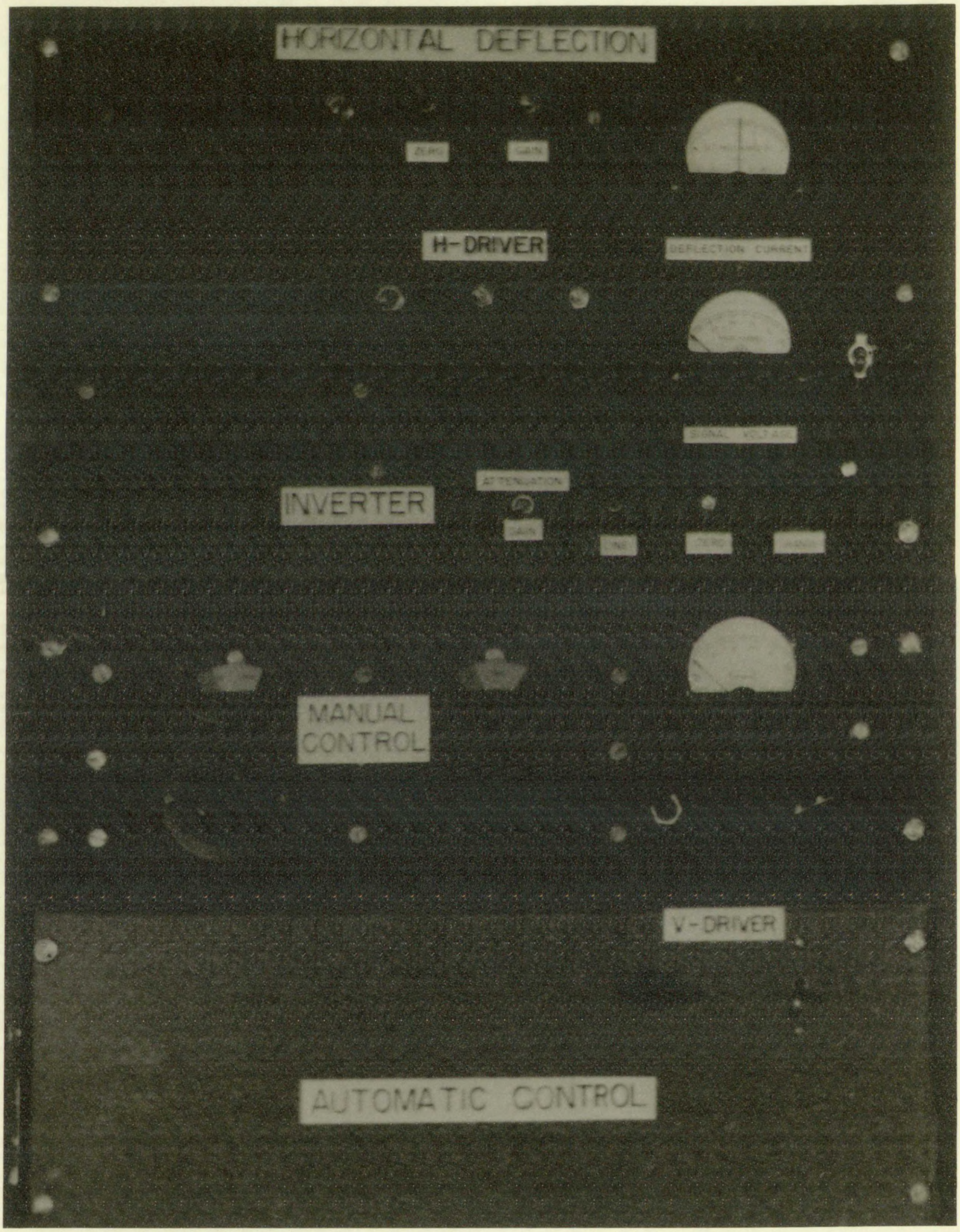
HORIZONTAL DEFLECTION
ZERO
GAIN
H-DRIVER
DEFLECTION CURRENT
SIGNAL VOLTAGE
ATTENUATION
INVERTER
GAIN
MANUAL
CONTROL
V-DRIVER
AUTOMATIC CONTROL

FIGURE 4

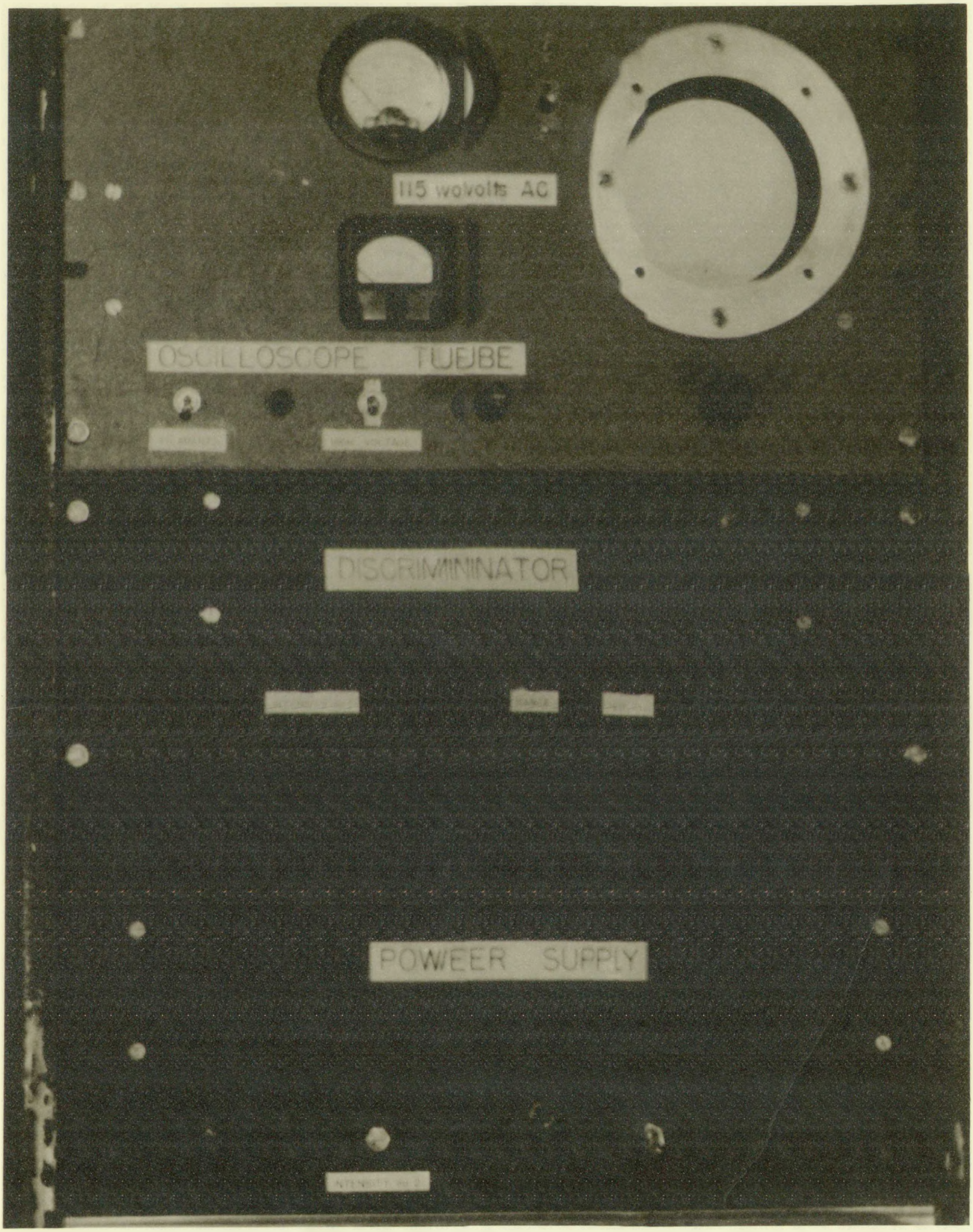
115 volts AC
OSCILLOSCOPE TUBE
DISCRIMINATOR
POWER SUPPLY

FIGURE 5

north through east, south, west, and back to north. The vertical driver was connected to the automatic control so that the spot would change its position up or down on the screen as the declination of the telescope changed. A photograph of the cathode-ray tube screen taken for one complete sweep of the sky would thus show horizontal lines whose intensity would be a measure of the intensity of the light in the corresponding region of the sky. The places where the intensity of the lines changed from a given value to another would indicate positions in the sky of equal luminosity. A line connecting these places would then be an isophote. Thus a representation of the zodiacal light could be obtained in the form of isophotes.

The Main Power Supply. A schematic diagram of this power supply is shown in Figure Six. The 200-270 volt outlet, which goes to grid No. 2 of the cathode-ray tube, was used as a secondary control of the intensity of the spot. As shown by the diagram all the power taken from the power supply was voltage-regulated.

The Voltage Inverter. Figure Seven shows a schematic diagram of the voltage inverter. The function of this unit is to invert the signal voltage and also to amplify or attenuate it by certain desired amounts. It is actually a

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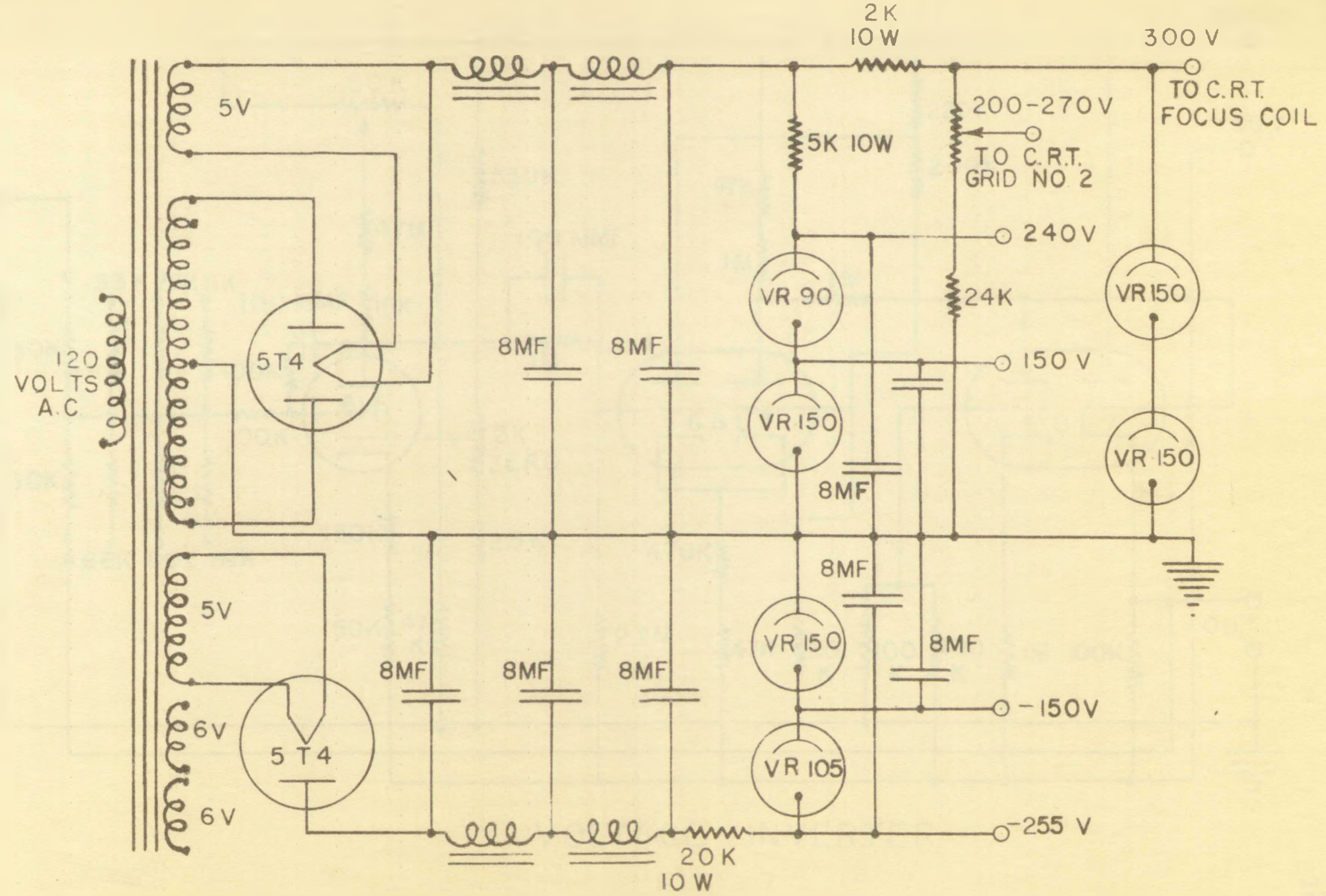
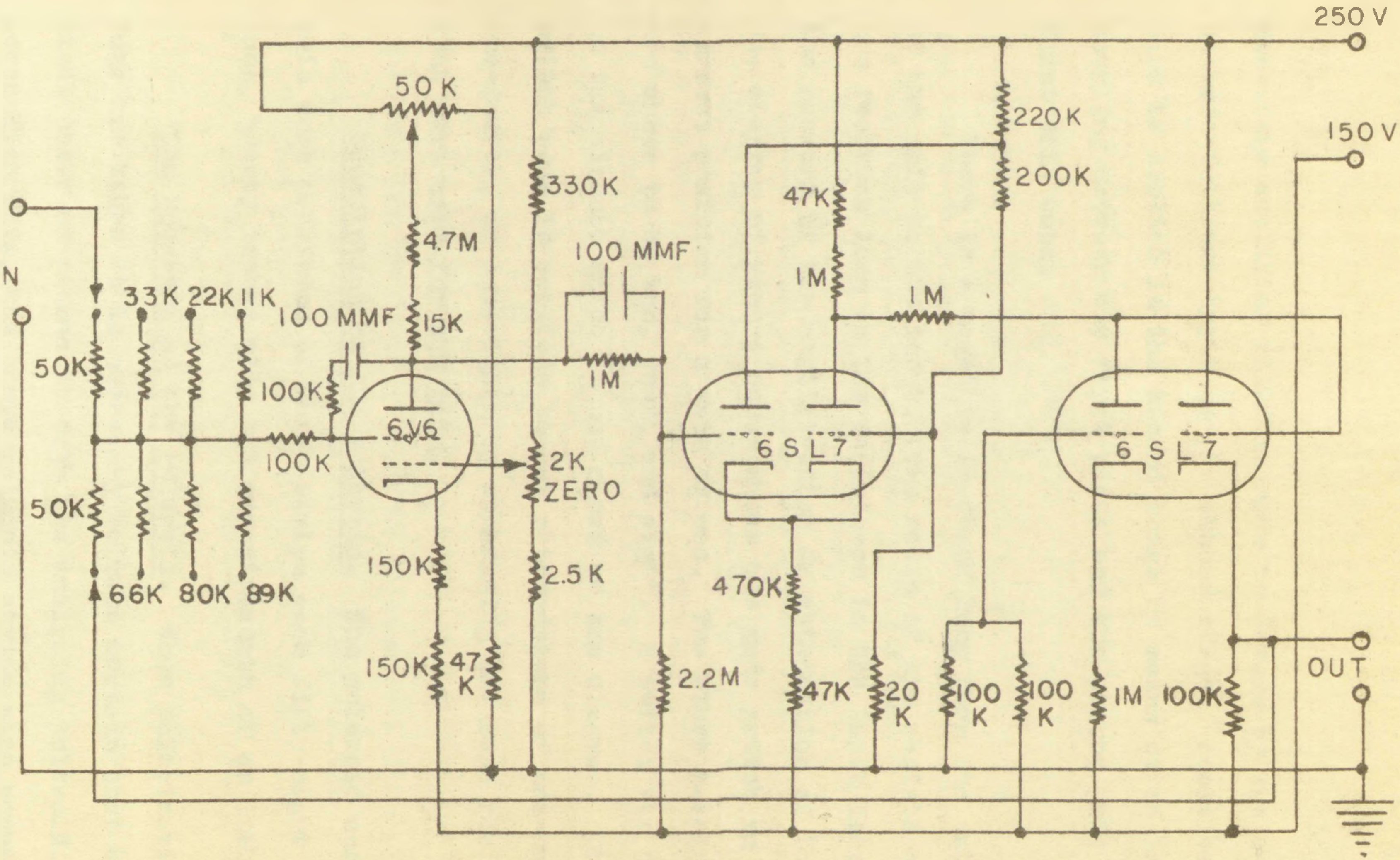


POWER SUPPLY

FIG. 6



VOLTAGE INVERTER

FIG. 7

two-stage amplifier which is made to invert by the use of a cathode-follower input to the second stage. Positive feedback is applied in the second stage by means of resistive coupling between the first plate and the second grid of the first 6SL7 tube.

There is a negative feedback loop from the output of the unit to the input. The ratio of the resistance in the feedback loop to the resistance in the input loop is the measure of the amplification or attenuation of the unit. The diagram of Figure Seven shows the gain switch in the correct position for a gain of one. The other possible gains are shown to be two, four, and eight. A switch was placed in the circuit which is not shown on the diagram. This switch made it possible to get attenuations of one-half, one-fourth, or one-eighth by exchanging the same resisters that were used for the gain.

<u>Description of the Polaroid</u>. The polaroid used for this work consisted of three strips each fifty-eight inches long, twenty inches wide and one-sixteenth of an inch thick.

<u>The Mounting of the Polaroid</u>. When polarization readings are taken it is necessary to make certain that all the light observed passes through the analyzing polaroid. To accomplish this, the three polaroid strips were mounted

two-stage amplifier which [illegible] is brought by means of a cathode-follower [illegible] to the [illegible]. [illegible] feedback is applied [illegible] coupling between the first plate and the [illegible] of the first 6SJ7 tube.

There is a [illegible] feedback loop from the output of the unit to the input. The ratio of the resistance in the feedback loop to the resistance in the input [illegible] the measure of the amplification [illegible]. The diagram of Figure [illegible] correct position for [illegible]. [illegible] are shown to be one, four, and eight. A switch was [illegible] in the circuit which [illegible] of the diagram. This switch made it possible [illegible] one-fourth, or one-eighth [illegible] that were used in the work.

<u>Description of [illegible]</u>. The polaroid [illegible] this work consisted of [illegible] twenty-eight inches long, twenty inches [illegible].

<u>The Mounting of the Polaroid</u>. [illegible] are taken [illegible] light [illegible] through the [illegible]. To accomplish this, [illegible]

together to form a rectangle fifty-eight inches by sixty inches. Half-inch aluminum angle strips were used to make this frame, which was then fastened to an aluminum ring, whose diameter corresponded to that of the telescope opening. The open places along the side of the polaroid were covered with thin aluminum sheets which were painted with lamp black to prevent reflection. In order to make space for the photo tube mount, eight seventeen inch standoffs were used to mount four steel rollers on which the ring could turn. Figure Two shows the searchlight with the mounted polaroid. Figure Eight shows the manner in which the ring was held in place by the rollers. Two of the rollers were spring loaded to facilitate the removal and replacement of the polaroid. The polaroid was rotated by hand.

Along the periphery of the movable ring, markers were spaced ten degrees apart. A stationary pointer was placed beside the ring to read in degrees the orientation of the plane of polarization of the polaroid. For a reading of zero the plane was perpendicular to the celestial equator or parallel to the hour circle which passed through the point under observation. Therefore, the reading for any position gave directly the angle between the hour circle of the observed point and the plane of polarization of the polaroid.

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Along the periphery of the [illegible] ring, markers were spaced ten degrees apart. A stationary pointer was placed beside the ring, so as to indicate the orientation of the plane of polarization of the polaroid. For a setting of zero the plane was perpendicular to the vertical circle or parallel to the long axis [illegible] through the point under observation. Therefore, the readings of the position gave directly the angle between the main circle of the observed point and the plane of polarization of the polaroid.

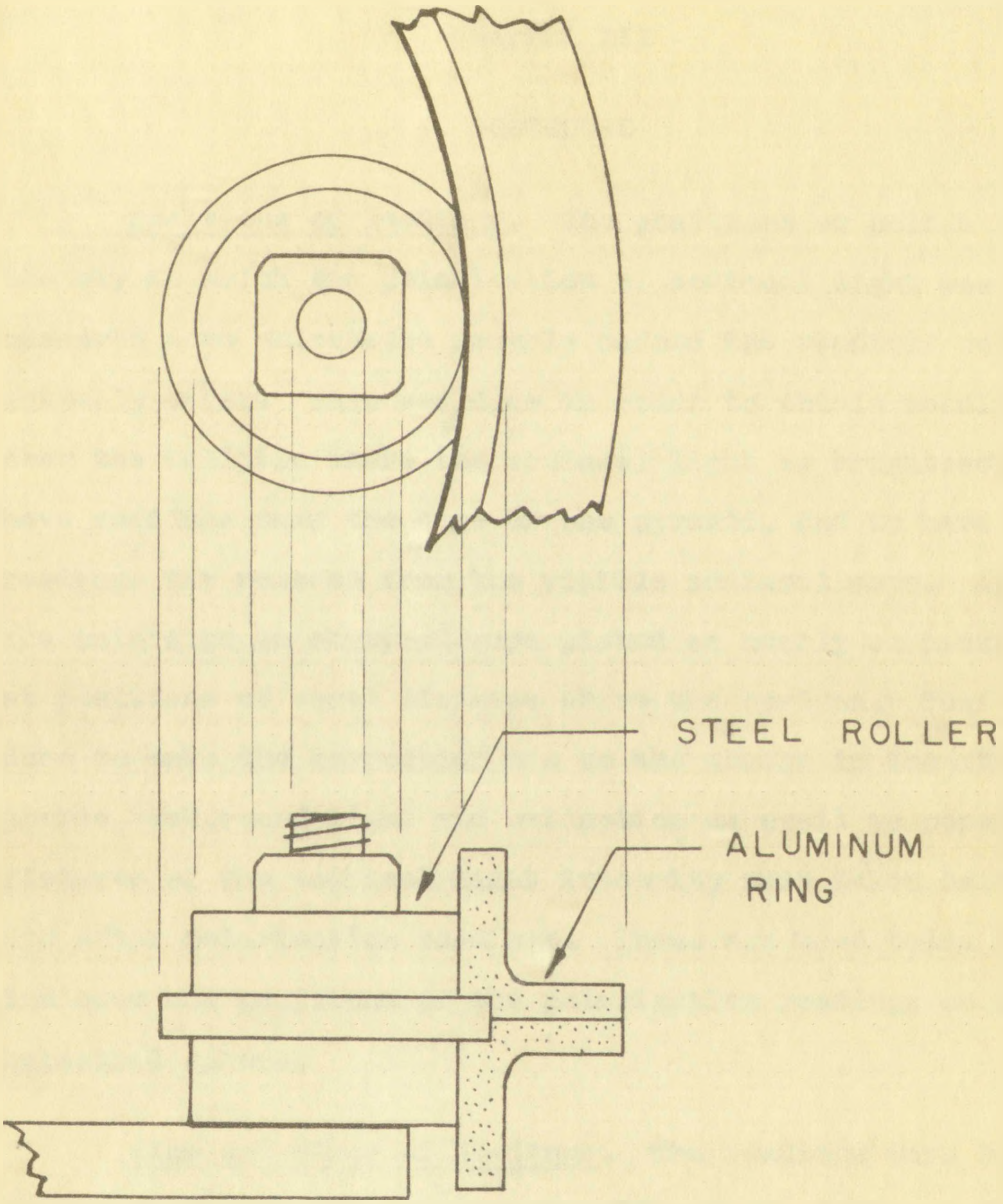

FIG. 8

CHAPTER III

PROCEDURE

Positions of Readings. The positions or points in the sky at which the polarization of zodiacal light was measured were calculated roughly before the readings were actually taken. This was done in order to obtain readings near the ecliptic where the zodiacal light is brightest, to have readings near the edge of the pyramid, and to have other readings far removed from the visible zodiacal cone. Also, the points to be observed were picked as nearly as possible at positions of equal distance above the horizon. This was done to make the correction due to the change in the atmospheric background light and extinction as small as possible. Pictures of the zodiacal light intensity were taken before and after polarization readings. These are used below to indicate the positions of the polarization readings on the celestial sphere.

Time and Place of Readings. The readings were taken in the early mornings of December 18 and 19, 1950, at the high altitude observatory of the Department of Physics, University of New Mexico, on Capillo Peak (9,200 ft.) in Torrance County, New Mexico. The moon made it impossible to observe the zodiacal light on the evenings of December 17 and 18; hence, the readings had to be taken during the

CHAPTER III

[illegible]

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Time and Place of Readings. The readings were taken in the early mornings of December 13 and 14, 1960, at the high altitude observatory of the Department of Physics, University of New Mexico, at Capilla Peak (9,200 ft.) in Torrance County, New Mexico. [illegible] to observe the zodiacal light on the evenings of December 17 and 18; hence, the [illegible] had to be taken during the

early hours of the following mornings. Since the positions of the sun, the horizon, and the ecliptic as well as the hour angle and the declination relative to the observed points had to be found, it was necessary to know and record the local sidereal time throughout the process of taking readings. To assure that one point of the sky was being investigated, the hour angle had to be increased at the rate of one degree for each four minutes of elapsed sidereal time. This was done by the manual remote controls and by the use of a clock which had been set to read local sidereal time.

Corrections for Background Light. Since zodiacal light is not the only contributing factor to the light of the night sky and any attempted measurement of zodiacal light would include the superimposed background light, corrections were made for this background. Corrections were also made for the fact that the background light varies in intensity with change in elevation above the horizon.

Calculations. Due to the fact that the starting time for readings and the amount of time necessary to complete readings at any one point could not be accurately predicted, the positions of the sun, horizon, and ecliptic relative to the point investigated had to be calculated after the readings had been taken.

early hours of the following morning. Since the positions of the sun, the horizon, and the zenith, as well as the hour angle and the declination [illegible] points had to be found, it was necessary to [illegible] the local sidereal time throughout the [illegible] readings. To [illegible] investigated, the [illegible] of one degree for [illegible] This was done by the [illegible] of a clock which [illegible]

Corrections [illegible]. [illegible] light [illegible] the night sky [illegible] light would [illegible] background light, corrections were made for [illegible] background. [illegible] were also made for [illegible] the background light varies in intensity [illegible] in elevation above the horizon.

Calculations. [illegible] time for readings and the amount of time necessary to complete [illegible] could be [illegible] predicted, the positions of the sun, the horizon, and [illegible] relative to the [illegible] had to be calculated [illegible] the readings had been made.

Method of Taking Readings. At least two persons were needed to obtain the polarization readings. One was stationed outside to rotate the polaroid and to relay the polaroid orientation readings to another stationed inside the observatory building at the panel shown in Figure Four. It was the task of the person inside to keep the same point in the sky in view by means of the manual control, and also to record the data. Telephone communication was established between inside and outside observers to coordinate the readings.

Taking the Data. The zodiacal light intensity readings were taken from the meter labeled "signal voltage" in Figure Four. The intensity of the light was noted for twelve different orientations of the polaroid while the telescope was held on one position in the sky. The orientations of the polaroid were spaced thirty degrees apart. The hour angle and local sidereal time were recorded for each of the twelve readings. The declination of the point which was investigated was recorded only once, since no change in it was needed to hold a given point in view due to the equatorial mounting of the telescope. The phototube screen aperture number and amplifier gain were also recorded. These two settings did not change throughout the reading.

Method of Taking the Data. At least two persons were needed to obtain the observations at night. One was stationed outside to make the [illegible] and the polaroid orientation readings on an [illegible] atop the observatory building at the [illegible]. It was the task of the [illegible] inside to read the star point in the sky in the [illegible] of the [illegible], as also to record the data. Telephone communication was maintained between inside and outside observers to coordinate the readings.

Taking the Data. [illegible] readings were taken from the [illegible] in [illegible] Park. The [illegible] of the [illegible] twelve different orientations of the polaroid [illegible] telescope are [illegible]. The orientations of the polaroid were [illegible]. The hour angle and local sidereal time were recorded for each of the twelve readings. The declination of the point which was [illegible] was recorded each time, [illegible] it was needed [illegible] point [illegible] to the [illegible] reading at the telescope. The [illegible] surface [illegible] were also recorded. [illegible] the reading.

Percentage of Polarization. If the light of the night sky is allowed to pass through an analyzing polaroid as the polaroid is being rotated through 180 degrees there will be an observed change in the intensity of the transmitted light. If M is the maximum intensity observed and N is the minimum intensity observed, then the percentage of polarization, p, of the incident night sky light is defined by:

$$p = \frac{M - N}{M + N} \cdot 100 \quad . \tag{1}$$

As has been previously stated, it is generally agreed that the zodiacal light is the only polarized component of the night sky light. One could therefore assume the percentage of polarization of zodiacal light, p_z, to be:

$$p_z = \frac{M - N}{M + N - 2x} \cdot 100 \quad , \tag{2}$$

where x is the combined intensity of all the unpolarized contributors to the night sky light, or the background light intensity.

Determination of Background Light. In this thesis two different methods were used to determine the background light intensity. In one method the intensity readings taken from points far removed from the zodiacal pyramid were assumed to be background light intensity readings. In

Percentage of Polarization. If the night sky light is allowed to pass through the analyzing polaroid as the polaroid is being rotated through 180 degrees, there will be an observed change in the intensity of the transmitted light. If M is the maximum intensity observed and m is the minimum intensity observed, then the percentage of polarization, p, of the incident night sky light is defined by:

$$p = \frac{M - m}{M + m} \cdot 100 \qquad (1)$$

As has been previously stated, it is not necessarily true that the zodiacal light is the only polarized component of the night sky light. To correct the above equation for the percentage of polarization of zodiacal light, p_z, we get,

$$p_z = \frac{M - m}{M + m - 2x} \cdot 100 \qquad (2)$$

where x is the combined intensity of all the unpolarized contributions to the night sky light, or the background light intensity.

Determination of Background Light. In this thesis two different methods were used to determine the background light intensity. In one method the intensity readings taken from points far removed from the zodiacal light were assumed to be background light for the adjacent points. In

other words, it was assumed that only a small percentage of the total intensity observed from these points was due to zodiacal light; therefore, any error involved would be small enough to be neglected. In the other method two points were chosen which had the same angular distance from the sun and the same elevation above the horizon, but different values of M and N. The percentage of polarization of the zodiacal light at the two points could then be assumed to be the same, and the background, x, could be found by:

$$\frac{M_1 - N_1}{M_1 + N_1 - 2x} = \frac{M_2 - N_2}{M_2 + N_2 - 2x} \qquad (3)$$

where the subscripts 1 and 2 denote values of M and N for the two different points.

other words, it was assumed that [illegible] a small percentage of the total [illegible] than those which was due to zodiacal light; therefore, any error involved would be small enough to be [illegible]. In the other method two points were chosen which had the same angular distance from the sun and the same altitude above the horizon, but different values of U and S. The percentage of polarization of the zodiacal light at the two points could then be assumed to be the same, and the unknown, x_1, could be found by:

[illegible]

where the subscripts 1 and 2 denote the values of U and S for the two different points.

CHAPTER IV

MEASUREMENTS AND ANALYSIS OF DATA

December 18, 1950. Figure Nine shows a photograph of the night sky light taken at 10:07 local sidereal time December 18, 1950. The numbers show the positions of the readings taken. The black lines are isophotes which are drawn in to show the approximate position of the zodiacal pyramid. As shown in the photograph, point No. 1 was near the center of the zodiacal pyramid, point No. 2 was near the edge, and No. 3 was a considerable distance from the intense zodiacal cone. Data for points No. 1, 2, and 3 will be shown in Tables I, II, and III respectively.

December 19, 1950. Im the early morning hours of December 19, 1950 readings were taken at points No. 4, 5, and 6. Since clouds obscured the sky up to an elevation of about twenty degrees above the horizon, the elevations of the points were relatively high. No photograph could be taken on this date due to the clouds. Point No. 4 was the only point of the three that was near the ecliptic. Tables IV, V, and VI show the data for the points No. 4, 5, and 6.

Fitting the Data to Theoretical Curves. The above

[illegible]

[illegible]

December 13, 1960. Figure [illegible] shows a photo-
graph of the [illegible] taken at [illegible] local [illegible]
time December 13, 1960. The arrows [illegible] the [illegible]
of the reading [illegible]. The [illegible] lines are [illegible]
are drawn in to show the approximate position of the [illegible]
cal spreads. As shown in the photograph, point No. 1 was
near the center of the [illegible], point No. 2 was
near the edge, and No. 3 was a [illegible] from
the intense [illegible] area. Data for points No. 1, 2, and
3 will be shown in Tables I, II, and III respectively.

December 14, 1960. [illegible]
December 14, 1960 readings were taken at points No. 4, 5,
and 6. Since clouds [illegible] up to an elevation of
about twenty degrees above the horizon, the elevations of
the points are relatively high. No photograph [illegible]
taken on which [illegible] point No. 4 was
the only point [illegible].
Tables IV, V, and VI show the data for points No. 4,
5, and 6.

Fitting the Data to Theoretical Curves. The above

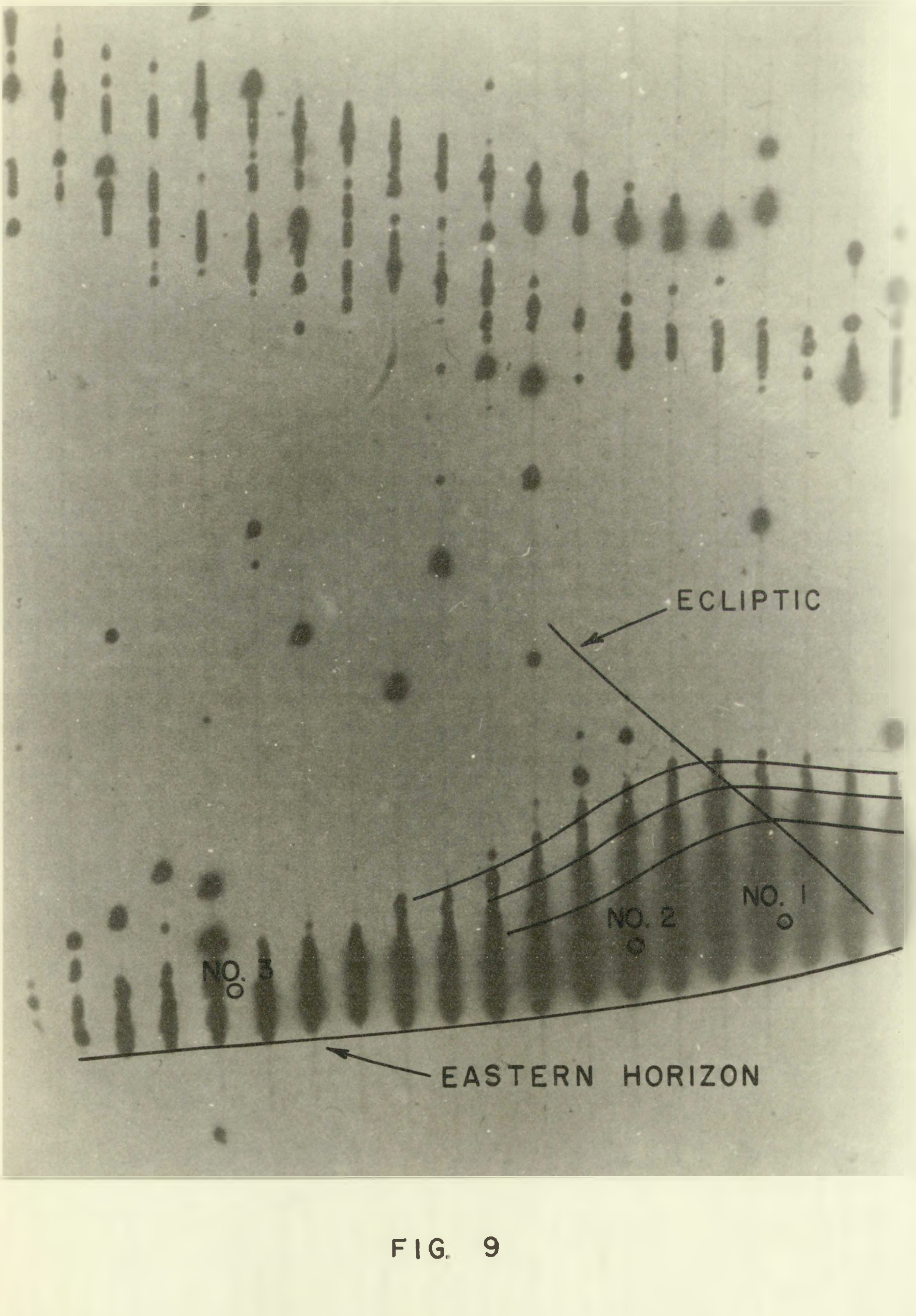

FIG. 9

TABLE I

POINT NO. 1

Date . . . . December 18, 1950

Elevation above horizon (average). . . . . 13°

Angular distance from the sun . . . . 38° 30'

The orientation of the plane of polarization of the polaroid when the plane of polarization passed through the sun (θ_o). . . . . 64°

Hour Angle	Declination	Local Sidereal Time	θ	y
293.5°	-10°	10:43	60°	2.8 volts
293.5			30	2.6
293.5			0	2.4
293.75		10:44	330	2.4
293.75			300	2.5
294.0		10:45	270	2.7
294.25		10:46	240	2.8
294.50		10:47	210	2.6
294.75		10:48	180	2.4
294.75			150	2.4
294.75			120	2.5
295.0		10:49	90	2.7

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

A	B	D	M	N	C	θ_m
2.56 v.	-1.5 v.	.14 v.	2.76 v.	2.36 v.	.205 v.	68°

$$\theta_o - \theta_m = -4^{\circ}$$

TABLE II

Point No. 2

Date . . . . December 18, 1950

Elevation above horizon (average) . . . . 14^{o}

Angular distance from the sun . . . . 37^{o}

The orientation of the plane of polarization of the polaroid when the plane of polarization passed through the sun (θ_o) . . . . 49^{o}

Hour Angle	Declination	Local Sidereal Time	θ	y
287.5^{o}	0^{o}	10:50	60^{o}	2.1 volts
.5			30	2.2
.75		10:51	0	2.0
.75			330	2.0
288.0		10:52	300	2.0
.0			270	2.2
.25		10:53	240	2.2
.25			210	2.2
.25			180	2.1
.5		10:54	150	2.0
.5			120	2.0
288.5			90	2.1

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

A	B	D	M	N	C	θ_m
2.1 v	-.03 v	.10 v	2.23 v	1.97 v	.128 v	53^{o}

$$\theta_o - \theta_m = -4^{o}$$

TABLE III

POINT NO. 3

Date . . . . December 18, 1950

Elevation above horizon (average). . . . . 12° 30'

Angular distance from the sun . . . . 50°

The orientation of the plane of polarization of the poleroid when the plane of polarization passed through the sun (θ_o) . . . . 11°

Hour Angle	Declination	Local Sidereal Time	θ	y
267.5°	26°	10:56	60°	1.65 volts
.5			30	1.7
.5			0	1.7
.5		10:57	330	1.65
268.0		10:58	300	1.6
.0			270	1.6
.0			240	1.65
268.25		10:59	210	1.7
.25			180	1.75
.25			150	1.7
.25			120	1.65
268.25			90	1.65

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

A	B	D	M	N	C	θ_m
1.67 v	.05 v	.01 v	1.72 v	1.62 v	.05 v	6°

$$\theta_o - \theta_m = 5^{\circ}$$

TABLE IV

POINT NO. 4

Date . . . . December 19, 1950

Elevation above the horizon (average) . . . . . . 38^{o} 30'

Angular distance from the sun . . . . 63^{o}

The orientation of the plane of polarization of the polaroid when the plane of polarization passed through the sun (θ_o) . . . . 67^{o}

Hour Angle	Declination	Local Sidereal Time	θ	y
325.0°	-6°	11:13	0°	4.8 volts
.0			330	4.8
.25		11:14	300	5.2
.25			270	5.8
.50		11:15	240	5.9
.50			210	5.5
.75		11:16	180	4.9
.75			150	4.8
326.0		11:17	120	5.2
.0			90	5.7
.0			60	5.8
326.0			30	5.4

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

A	B	D	M	N	C	θ_m
5.31 v	-.44 v	.375 v	5.89 v	4.73 v	.58 v	70°

$$\theta_o - \theta_m = -3^{o}$$

TABLE V

POINT NO. 5

Date . . . . December 19, 1950

Elevation above horizon (average) . . . . 45^{o}

Angular distance from the sun . . . . 104^{o} 30'

The orientation of the plane of polarization of the polaroid when the plane of polarization passed through the sun (θ_o) . . . . 43^{o}

Hour Angle	Declination	Local Sidereal Time	θ	y
310.0^{o}	70^{o}	11:19	0^{o}	2.6 volts
.0			330	2.6
.25		11:20	300	2.4
.25			270	2.6
.50		11:21	240	2.6
.50			210	2.6
.50			180	2.6
.50			150	2.5
.75		11:22	120	2.4
.75			90	2.6
.75			60	2.8
311.0		11:23	30	2.8

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

A	B	D	M	N	C	θ_m
2.6 v	-.06 v	.10 v	2.71 v	2.49 v	.11 v	60^{o}

$$\theta_o - \theta_m = -17^{o}$$

TABLE VI

POINT NO. 6

Date . . . . December 19, 1950

Elevation above horizon (average). . . . . 16°

Hour Angle	Declination	Local Sidereal Time	θ	y
260.0°	40°	11:25	0°	3.1 volts
.0			330	3.1
.0			300	3.1
.0			270	2.7
.0			240	2.5
.25		11:26	210	2.2
.25			180	2.3
.25			150	2.5
.50		11:27	120	2.5
.50			90	2.4
.50			60	2.8
260.50			30	3.5

θ = The angle of orientation of the plane of polarization of the polaroid.

y = Light intensity.

mentioned data were used to plot curves of light intensity as a function of the orientation of the plane of polarization of the polaroid. An intensity reading was taken for each thirty degree interval as the polaroid was rotated through 360 degrees as shown by the Tables and by the curves on Figures Ten, Eleven, and Twelve.

The physical characteristics of the method lead one to expect the following type of curve for the light intensity as a function of the orientation angle of the polaroid screen:

$$y = A + B \cos 2\theta + D \sin 2\theta \,, \qquad (4)$$

where y is the light intensity observed at the orientation of the plane of polarization of the polaroid, θ. To get the best curve of the above type to fit the twelve experimental readings at each of the observed points in the sky, the value of A, B, and D had to be found for each curve drawn.

The method of least squares was used for this purpose and the values of A, B, and D that were to be obtained are:

$$A = \frac{\sum_{n=1}^{n=12} y_n}{12} \,, \qquad (5)$$

mentioned data were used to plot curves 1-31 in Appendix, as a function of the orientation of the plane of polarization of the polaroid. The intensity reading was taken for each thirty degrees rotation as the polaroid was rotated through 360 degrees as shown by the tables and by the curves on Figures Ten, Eleven, and Twelve.

The physical characteristics of the problem lead one to expect the following type of curve for the light intensity as a function of the orientation angle of the polaroid screen:

$$I_\theta = A + B\cos 2\theta + C\sin 2\theta$$

where I_θ is the light intensity observed at the orientation of the plane of polarization of the polaroid, θ. To get the best curve to fit the points [illegible] The twelve experimental readings at each of the observed points in the sky, the value of A, B, and C had to be found for each curve drawn.

The method of least squares was used for this purpose and the values of A, B, and C that were then obtained were:

$$\frac{\sum_{i=1}^{12} I_i}{12} \qquad (13)$$

$$B = \frac{\sum_{n=1}^{n=12} y_n \cos 2\theta}{\sum_{n=1}^{n=12} \cos^2 2\theta} , \tag{6}$$

$$D = \frac{\sum_{n=1}^{n=12} y_n \sin 2\theta}{\sum_{n=1}^{n=12} \sin^2 2\theta} . \tag{7}$$

The amplitude, C, can then be obtained by:

$$C = \sqrt{B^2 + D^2} . \tag{8}$$

The value of the maximum reading, M, and the minimum reading, N, for any given point is obtained from

$$M = A + C \tag{9}$$

$$N = A - C . \tag{10}$$

The θ which gave a maximum intensity reading, θ_m, is found by setting the derivative of y with respect to θ equal to zero. The values of these constants for each point are shown in Tables I through VI.

The curves and positions of experimental readings for points No. 1, 2, and 3 are shown in Figure Ten. The curves for points No. 4 and 5 are shown in Figures Eleven and Twelve respectively.

Elevation Corrections. In the morning of December

$$D = \frac{\dots}{\dots} \qquad (6)$$

$$E = \frac{R_{\dots} \sin 2\theta}{\sin 2\theta} \qquad (7)$$

The amplitude, C, can then be obtained by:

$$C = \sqrt{D^2 + E^2} \qquad (8)$$

The value of the maximum deflection, M, and the minimum dial reading, N, for any given point is obtained then

$$M = A + C \qquad (9)$$

$$N = A - C \qquad (10)$$

The θ which gives a maximum is denoted by constant, θ_m, is found by setting the derivative of y with respect to θ equal to zero. The values of [illegible] for each point are shown in Tables [illegible].

The curves and results of experimental readings for points 0, 1, 2, and 3 are shown in Figure 8a. The curves for points [illegible] and [illegible] are shown in Figures [illegible] and [illegible] respectively.

Dimension corrections. In the analysis of [illegible]

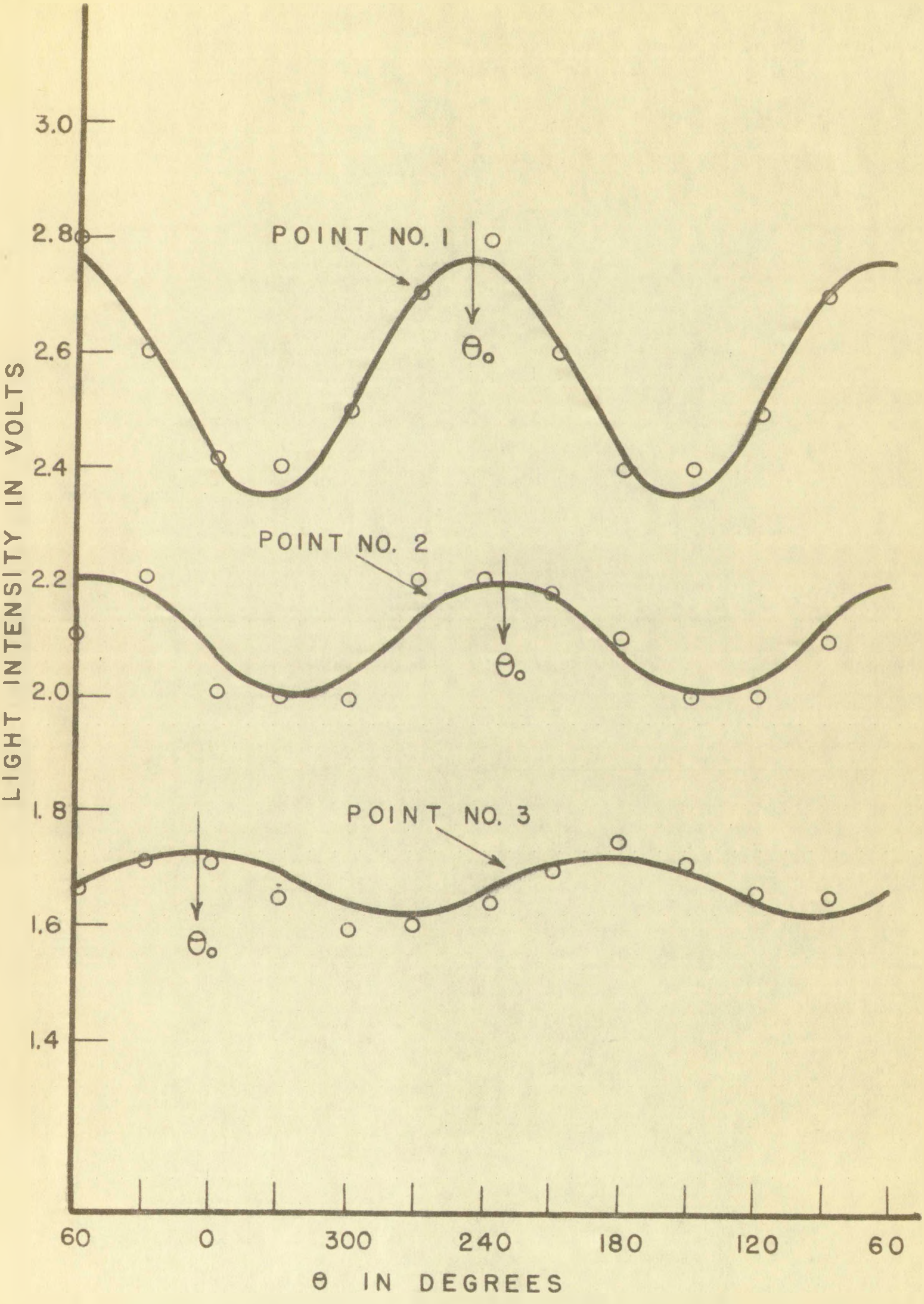
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
LIGHT INTENSITY IN VOLTS
POINT NO. 1
POINT NO. 2
POINT NO. 3
θ_o
θ_o
θ_o
60
0
300
240
180
120
60
θ IN DEGREES

FIG. 10

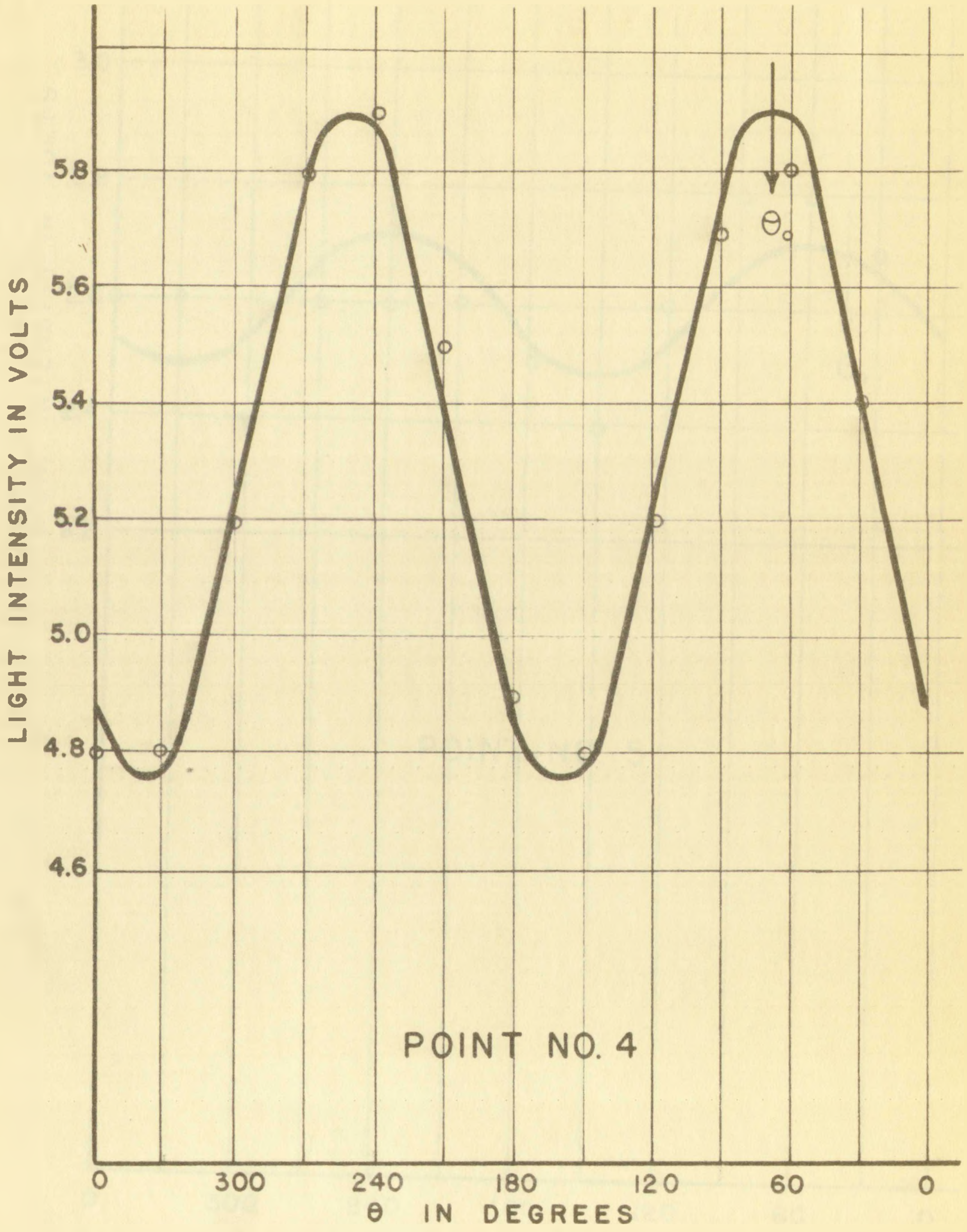
LIGHT INTENSITY IN VOLTS
5.8
5.6
5.4
5.2
5.0
4.8
4.6
θ₀
POINT NO. 4
0
300
240
180
120
60
0
θ IN DEGREES

FIG. 11

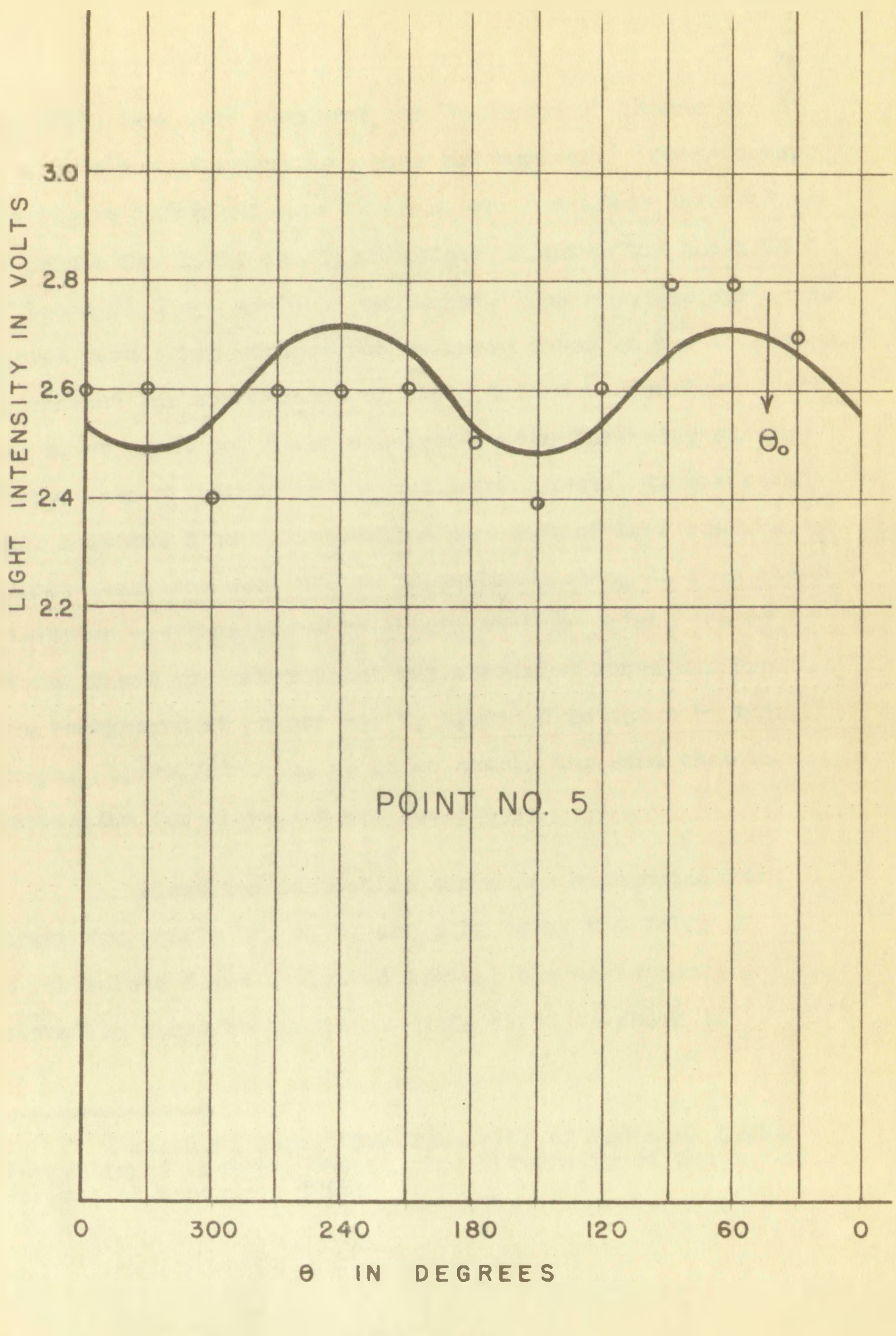
3.0
2.8
2.6
2.4
2.2
LIGHT INTENSITY IN VOLTS
θo
POINT NO. 5
0
300
240
180
120
60
0
θ IN DEGREES

FIG. 12

18, 1950, data were obtained for "background" intensity as a function of elevation above the horizon.[9] These data, see Figure Thirteen, were taken before and after the readings at points No. 1, 2, and 3; therefore, a curve for the time of these readings could be estimated. The readings for these curves were taken without the polaroid cover on the telescope. To correct for the absence of the polaroid the maximum reading M, at point No. 3 was compared to the intensity reading at the same elevation on the estimated curve. It was found that M at No. 3 was thirty-three per cent of this reading. Thirty-three per cent of the intensity reading at some other elevation was then taken to obtain another point. Using M at No. 3 and the other point the corrected curve was drawn. The background at points No. 1, 2, and 3 is shown by this graph, Figure Thirteen, to be so nearly the same that no correction for elevation was necessary.

An elevation correction curve for background was drawn for points No. 4, 5, and 6 by using the value of A for points 5 and 6 plotted against the corresponding elevation above the horizon. This curve is shown in

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9 Allan F. Beck, "The Intensity of Zodiacal Light" (unpublished Master's thesis, The University of New Mexico, Albuquerque, 1951)

15, 1960, data were obtained of "background" intensity as a function of elevation above the horizon.[9] These data, one figure per [illegible], were taken before and after the readings at points No. [illegible], and [illegible], so that a curve for the [illegible] of these readings could be [illegible]. [illegible] curves were taken through the [illegible] and [illegible]. To correct for the elevation of the point in the surface reading, [illegible] at point No. [illegible] was compared to the intensity reading at the same elevation on the [illegible] curve. It was found that [illegible] the [illegible] of each reading. [illegible] of the intensity reading of the [illegible] elevation [illegible] angles of points. [illegible] The [illegible] points No. [illegible], and [illegible] graph, Figure [illegible]. [illegible] the same that no correction for elevation was necessary.

An elevation correction curve for background was drawn for points No. 4, 5, and 6 by [illegible] the [illegible] for points [illegible] against the corresponding elevation [illegible]. This curve is shown in

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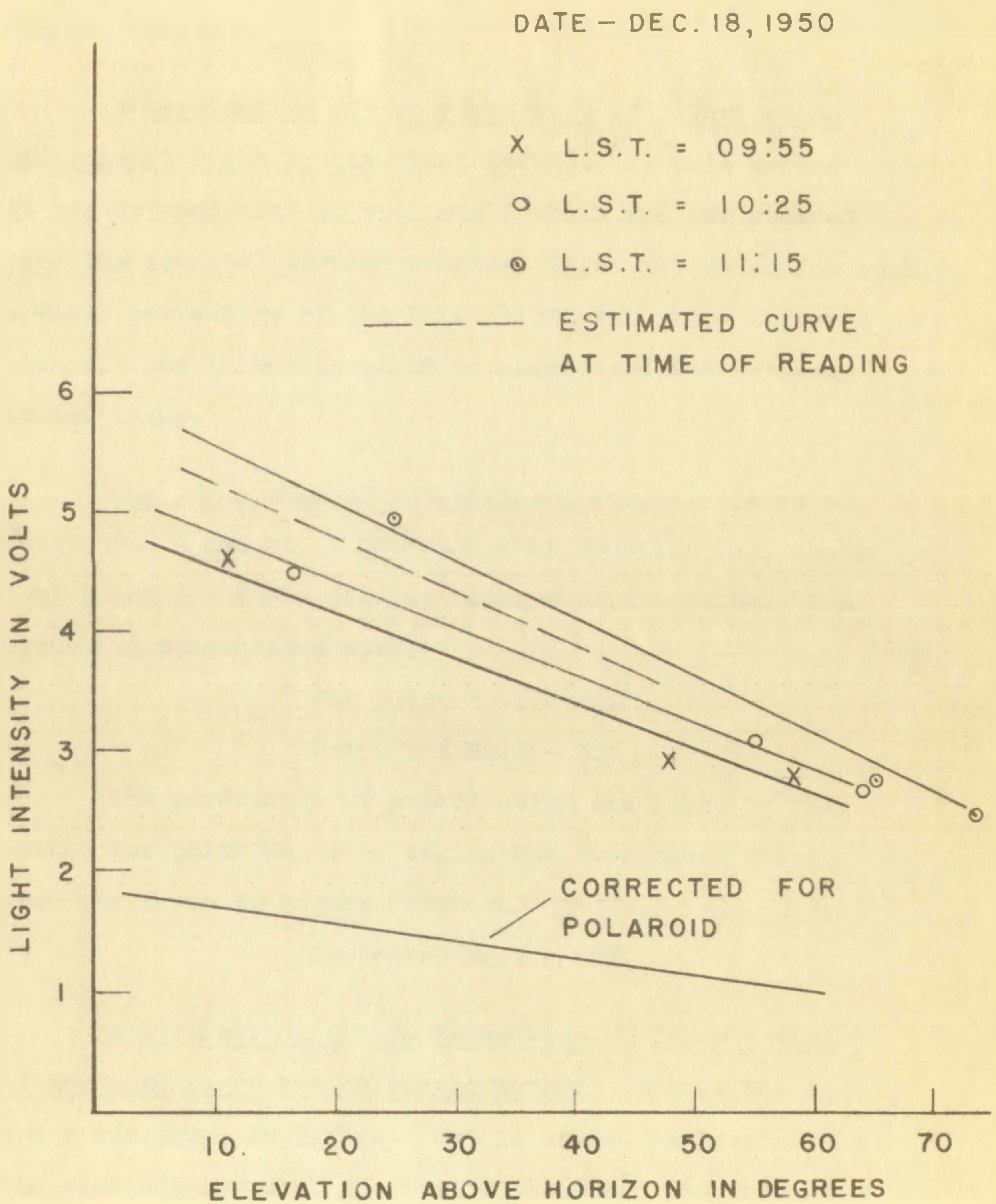
9 Allan [illegible], "[illegible] Intensity of [illegible] Light" (unpublished [illegible], University of New Mexico, Albuquerque, 1960)



BACKGROUND CURVE

FIG. 13

Figure Fourteen.

Determination of the Percentage of Polarization of Zodiacal Light by the First Method. In this method it was assumed that at the points which are far removed from the zodiacal pyramid zodiacal light accounted for such a small percentage of the total light intensity observed that all the intensity could be considered due to background light.

The percentage of polarization was calculated at points No. 1 and No. 2 by the use of equation (2), where A of point No. 3 was used as background intensity. The resulting percentages were:

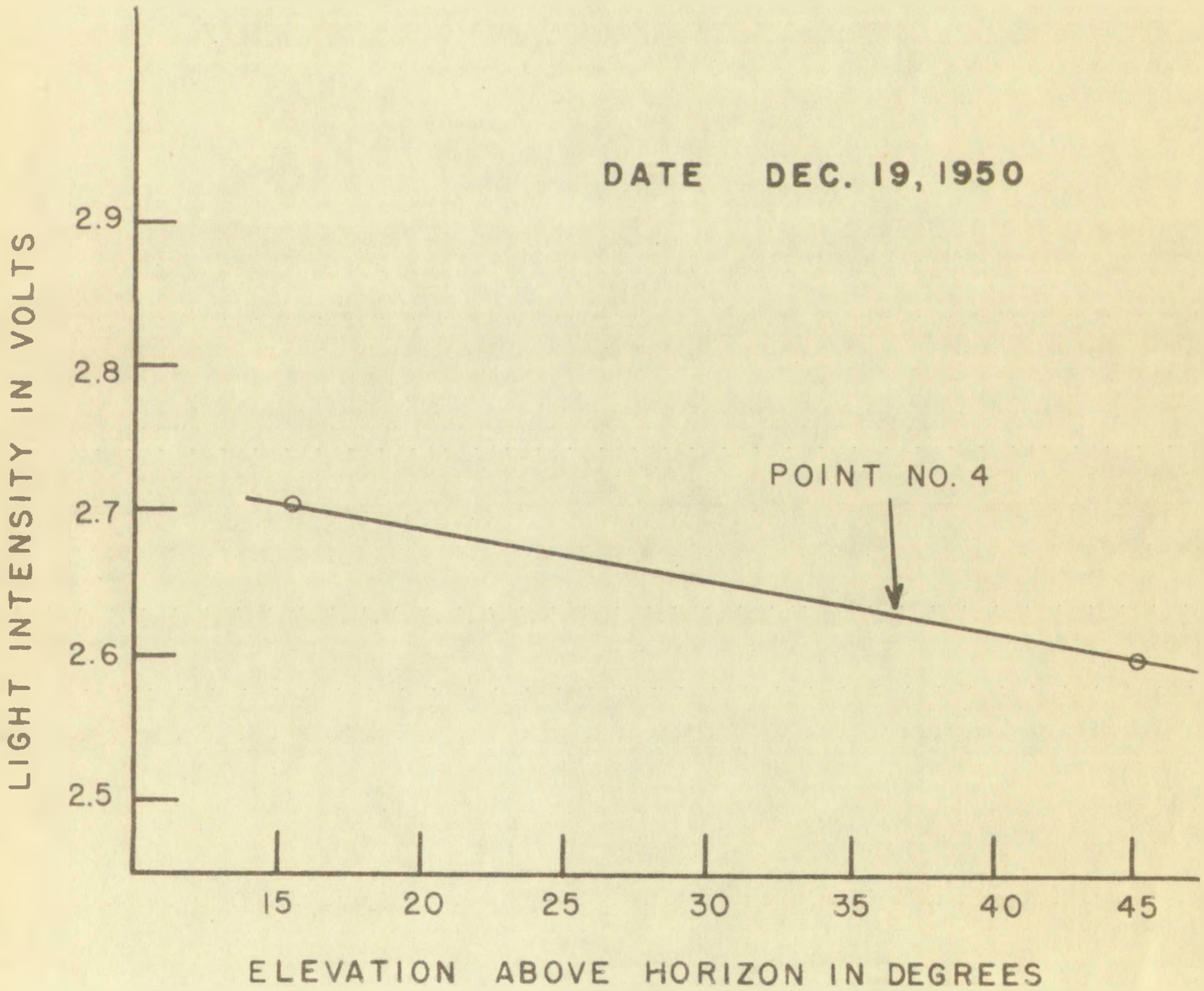
For point No.1 - 23%

For point No.2 - 30%

The percentage of polarization was found by this method for point No. 4 by taking the background value from the curve in Figure Fourteen.

For point No.4 - 22%

Determination of the Percentage of Polarization of Zodiacal Light by the Second Method. Points No. 1 and 2 are shown in Tables I and II to have approximately the same angular distance from the sun and the same elevation above the horizon. One would expect the zodiacal



BACKGROUND CURVE

FIG. 14

light at these points to have the same percentage of polarization to the first approximation. Thus, equation (3) was used to determine the background at points 1 and 2. Using this value of the background, equation (2) was used to find the percentage of polarization of the zodiacal light at these points.

Since point No. 3 had the same elevation above the horizon as No. 1 and No. 2, the same background could be used to find the percentage of polarization of the zodiacal light at point No. 3. The percentages obtained by this method were:

For point No.1 - 15%

For point No.2 - 15%

For point No.3 - 13%

Since point No. 3 has a greater angular distance from the sun than points 1 and 2, one would conclude from the above results that points 1 and 2 are closer to the angular distance from the sun which gives maximum polarization. Unfortunately, however, the intensity readings at point No. 3 were subject to an appreciable error because they were too low to be read accurately on the signal voltage meter.

Of the three points investigated on December 19, 1950 only the readings of points No. 4 and No. 5 could be fitted to curves. Since points No. 4 and 5 were not the same

angular distance from the sun, this method of determining the percentage of polarization could not be strictly applied. However, equation (3) was used to find the background which gave an "average" percent of polarization for these points.

For point No.4 - 18%

For point No.5 - 18%

Since points No. 4 and 5 were both a greater angular distance from the sun than No. 1 and 2 an increase in percentage of polarization with increased angular distance from the sun is indicated.

Direction of the Plane of Polarization. When analyzing plane polarized light, the maximum transmission of light occures when the plane of polarization of the light and the plane of polarization of the analyzer are parallel. As shown by the Tables of the points investigated, the maximum of the best fitted curve always occurred at an angle, θ_m, which was very near to the angle at which the plane of polarization of the polaroid passed through the sun, θ_o. The difference between θ_o and θ_m is shown in the Tables. Fluctuations in the night sky light intensity that took place during the polarization measurements could account for a shift of the maximum point on the curve which would explain the difference between θ_o and θ_m. With the exception of this difference which was small in almost

angular dispersion [illegible] the [illegible] this method of calculating the percentage of [illegible] would not be [illegible]. However, when [illegible] the [illegible] with gave an [illegible] for [illegible]

[illegible]

[illegible]

Since points are [illegible] angular distance from the [illegible] a_1 [illegible] is expressed in percentage of polarization [illegible] angular distance from the sun in this case.

Direction of the plane of polarization. [illegible] plane polarized [illegible] light, occurs when the plane of polarization of the light and the plane of [illegible] the analyzer are parallel. As shown by the tables of the [illegible], the readings of the [illegible] a [illegible] angle, ϕ_1, [illegible] the angle at which the plane of polarization [illegible] passed through the sun, ϕ_2. The difference between ϕ_1 and ϕ_2 is shown in the tables. [illegible] the [illegible] would [illegible] ϕ_1 and ϕ_2 [illegible]

every case, the plane of polarization of zodiacal light was found to pass through the sun.

CHAPTER V

CONCLUSIONS

Percentage of Polarization. The background of 1.25 volts used in the second method to make the percentage of polarization at points No. 1 and 2 equal indicates that even at point No. 3 which was well outside the clearly visible zodiacal cone, zodiacal light makes up over twenty-eight per cent of the night sky light. This indicates that of the two methods used to determine the percentage of polarization from the collected data, the second method is preferable.

Nature of the Particles. The percentage of polarization would seem to be too high to be caused by reflection from the surface of large planetary dust particles or bodies. It can be assumed then that the polarization observed is a result of Rayleigh scattering and that the scattering particles are of molecular dimensions. It should be possible to gain important information concerning the nature and position of the zodiacal cloud by further investigations of the variations of the percentage of polarization of zodiacal light as a function of angular distance from the sun.

CHAPTER VI

SUMMARY

Summary. A large polaroid strip was placed over the opening of the telescope on a mounting which enabled it to be rotated. A photomultiplier tube which was mounted at the focus of the mirror of the telescope converted the light intensity into an electrical signal which could be measured. When the telescope was directed at a given point in the night sky, the light intensity was read for known orientations of the plane of polarization of the polaroid. The percentage of polarization as well as the orientation of the plane of polarization of zodiacal light was calculated from the data obtained.

It was found that the percentage of polarization of zodiacal light was fifteen, thirteen, and eighteen per cent for angular distances from the sun of thirty-seven, fifty, and seventy-two degrees, respectively. The plane of polarization of zodiacal light was found to pass very nearly through the sun, the deviations being minus four, minus four, and plus five degrees.

Summary. A [illegible] was placed over the opening of the telescope [illegible] a [illegible] which [illegible] to be rotated. A [illegible] at the focus of the [illegible] light intensity into an electrical signal which could be measured. When the telescope was directed at a given point in the sky, [illegible] for each [illegible] of the plane of polarization of the [illegible]. The [illegible] of polarization [illegible] and the orientation of [illegible] were [illegible] from the data obtained.

It was found that [illegible] percentage of polarization of [illegible] light [illegible], and although [illegible] for [illegible] thirty-seven, fifty, and [illegible]. The [illegible] of polarization [illegible] was found to [illegible] very [illegible], the [illegible] forty, ninety four, and [illegible].

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