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DESIGN OF A BREADBOARD REMOTE OCULOMETER

by Kenneth A. Mason and John Merchant

Prepared by
HONEYWELL RADIATION CENTER
Lexington, Mass.
for Electronics Research Center

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HONEYWELL RADIATION CENTER
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DESIGN OF A BREADBOARD REMOTE OCULOMETER

Kenneth A. Mason
John Merchant

December 1968

Honeywell Radiation Center
Lexington, Massachusetts

INTRODUCTION

An Oculometer is an electro-optical device that measures the pointing direction of the human eye. It performs this measurement without any attachment to the subject, and operates with essentially invisible infrared radiation. In the first phase of NASA Contract NAS 12-531, a laboratory Oculometer was designed and fabricated in a proximate configuration. This device consists of an optomechanical unit and an electronics unit. In operation, the eye looks through a dichroic beamsplitter located at one end of the unit (see Figure 1 a). The eye is illuminated by an infrared source within the unit. An image of the eye is formed at the photocathode of the image dissector tube which is also within the optomechanical unit. The electronics unit processes the video signal from the image dissector, and generates appropriate scan signals causing the dissector to search for, acquire, and track the image of the eye that is formed at the photocathode. Eye direction information is derived from this electronic tracking system. The field of view at the eye for the proximate Oculometer is about 1.2 in. in diameter.

Another version of the Oculometer, called the remote Oculometer, is shown in Figure 1 b. Here the optics are designed such that the eye is tracked when it is several feet from the device; otherwise

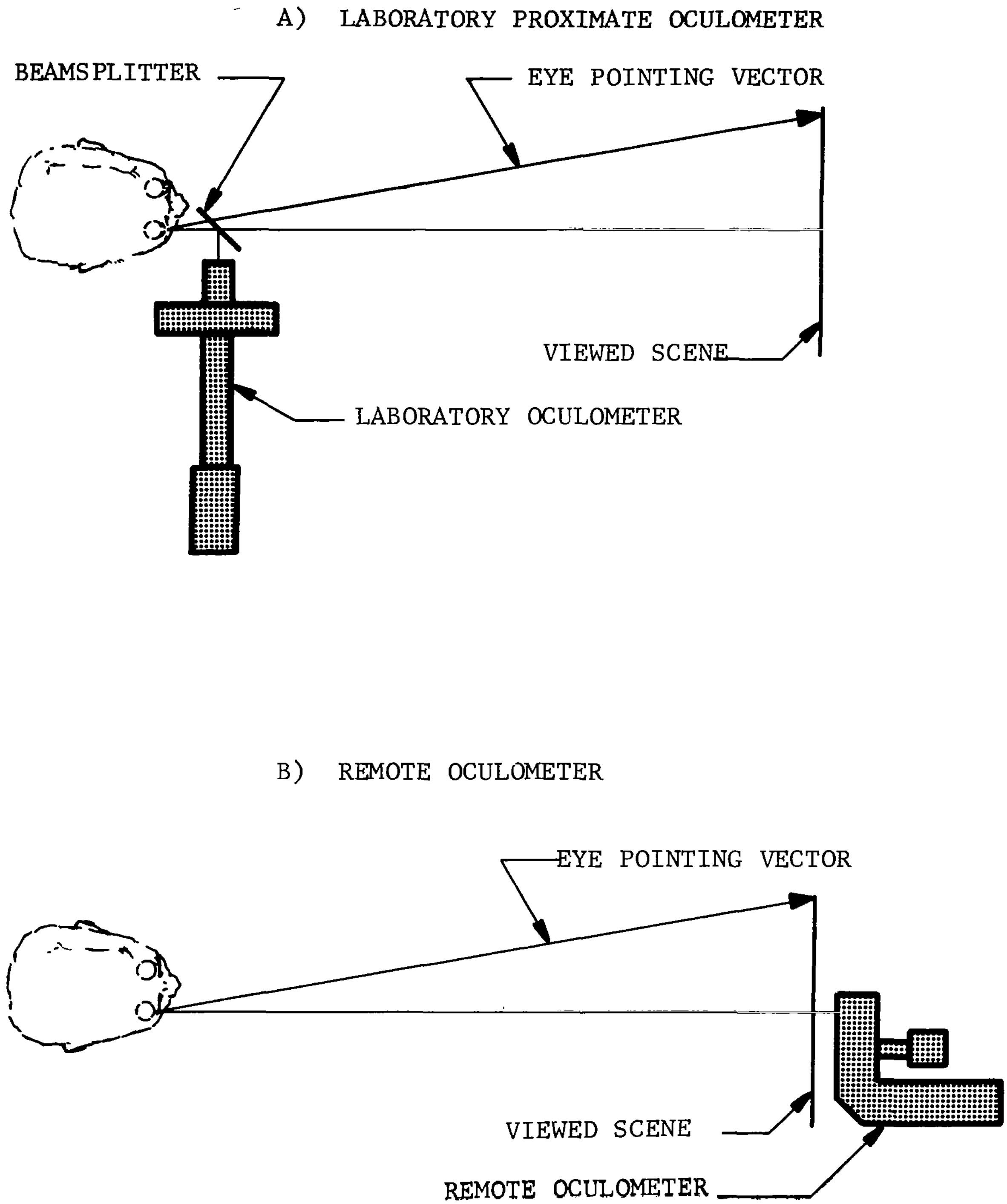


Figure 1 TWO OCULOMETER CONFIGURATIONS

the two versions of the Oculometer are the same. If the remote version of the Oculometer is used, a moving mirror may be utilized so as to move the field of view of the instrument (typically 1-inch diameter) in synchronism with the head movements of the subject. Thereby the device can measure eye direction under a reasonably large range of lateral head movement by the subject. The remote Oculometer thus offers significant advantage where, (1) the measuring device must be located several feet from the subject, and (2) where the subject must be afforded a large range of lateral head movement.

In order to prove the feasibility of the remote Oculometer concept, a breadboard of the device was designed and fabricated. Specifically, this involved the design and fabrication of (1) a new optomechanical unit appropriate to the remote Oculometer, (2) a two-axis moving mirror assembly and (3) an additional electronics unit with which to control the moving mirror rotation angles. When the above three items were completed they were integrated with the electronics unit originally built for the laboratory Oculometer. Testing of the assembled remote Oculometer indicated that the expected performance had been achieved. Figures 2, 3, and 4 are photographs of the breadboard device (exclusive of the laboratory Oculometer electronics). This document describes the design of the optics and the moving mirror subsystem that were required for the breadboard remote Oculometer.

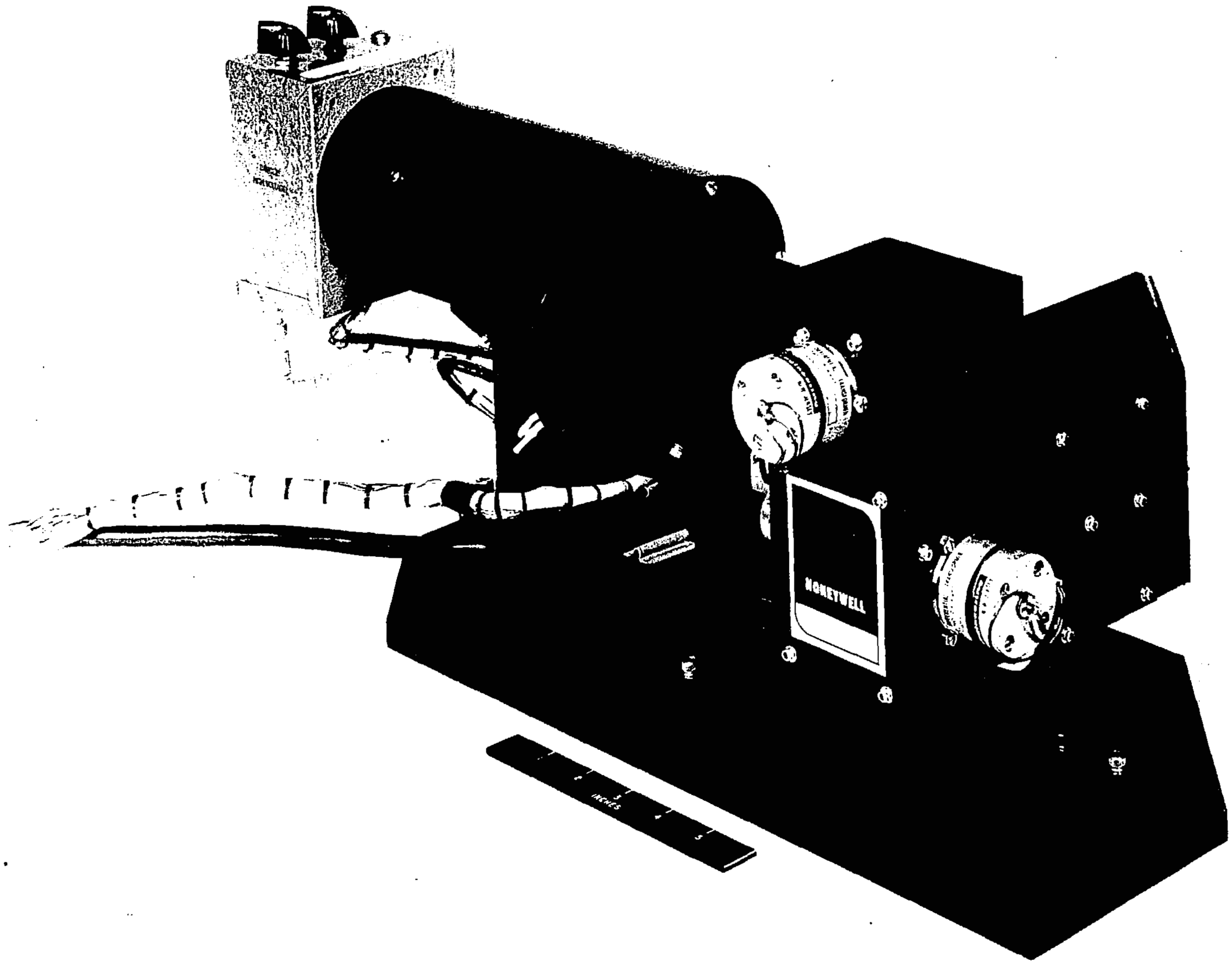


Figure 2 BREADBOARD REMOTE OCULOMETER: OPTO-MECHANICAL ASSEMBLY

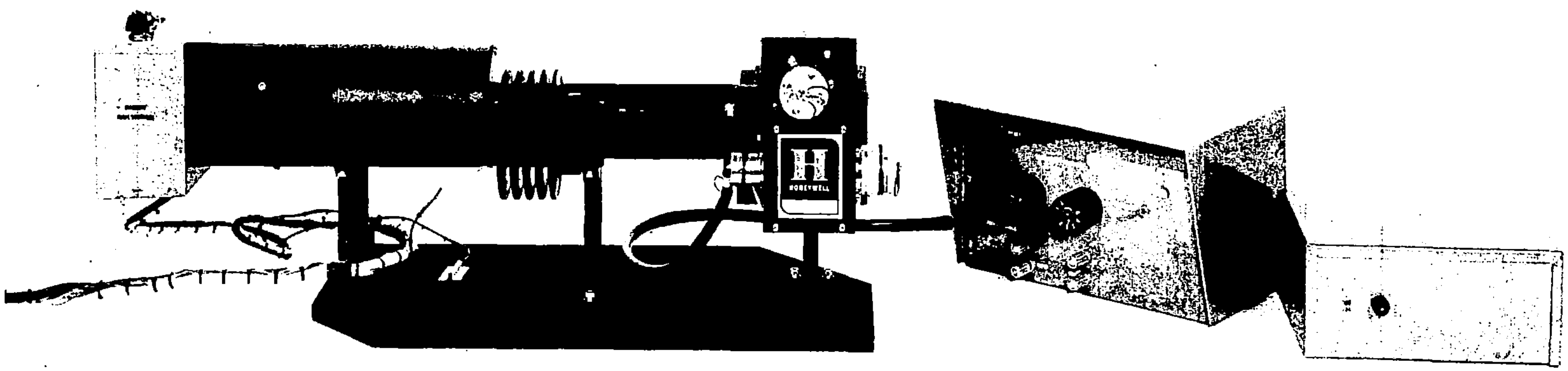


Figure 3 BREADBOARD REMOTE OCULOMETER: OPTO-MECHANICAL ASSEMBLY AND MIRROR CONTROL ELECTRONICS

Figure 4 SUBJECT BEING MONITORED BY BREADBOARD REMOTE OCULOMETER

GENERAL PRINCIPLE OF REMOTE OCULOMETER

Basic Operation

In the operation of the remote Oculometer, the eye is illuminated by an infrared source, and the eye area is imaged onto the sensitive area of an image sensor. The two features of the eye that appear brightly in the eye image are (a) the pupil of the eye and (b) the corneal reflection, i.e., the reflection of the illumination source that is formed by the eye's cornea. A photo of the eye image is shown in Figure 5. The image sensor scans the boundary of the pupil and the corneal reflection. A measurement of the distance between the pupil centroid and the corneal reflection centroid is thereby made. The geometry of the Oculometer optics and the eye optics is such that this distance is proportional to the subject's eye pointing direction. In the remote Oculometer configuration, this distance is proportional to the angle θ between the eye pointing vector and the vector between the eye and the collection aperture of the device; this is shown in Figure 6. Thus, if the eye is fixating at a given object and the head moves in the eye space, the Oculometer output will not change. A complete discussion of the relation between eye direction and the pupil-corneal reflection distance is presented in Interim Report: System Design Study For An Optimal Remote Oculometer For Use In Operational Aircraft. It should be noted, that in the laboratory (or proximate) Oculometer design, the pupil-corneal reflection separation is proportional to the angle ψ between the eye direction vector and the device optical axis. With reference to Figure 6 this angle ψ is equal to ($\theta - \phi$).

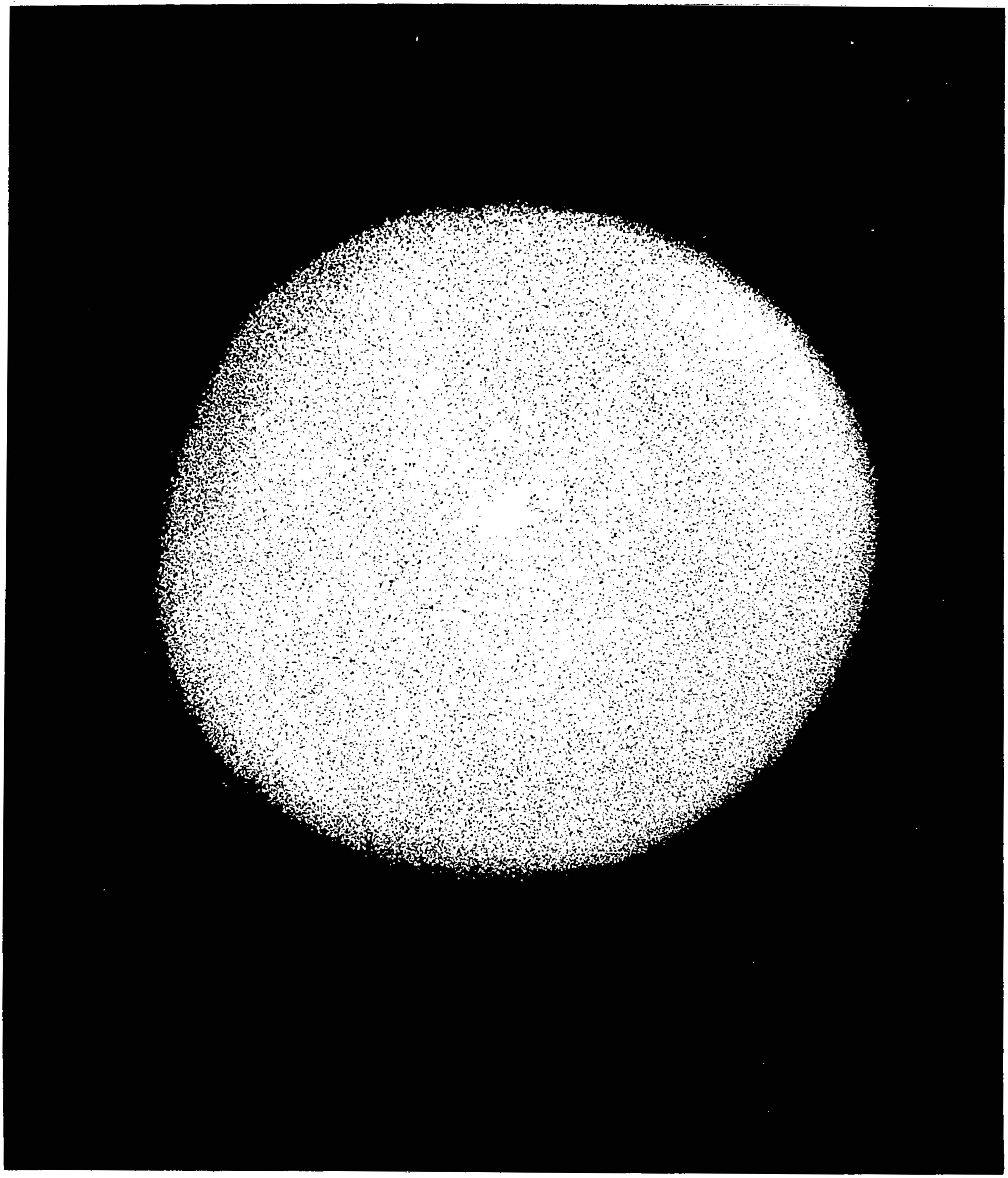


Figure 5 EYE IMAGE

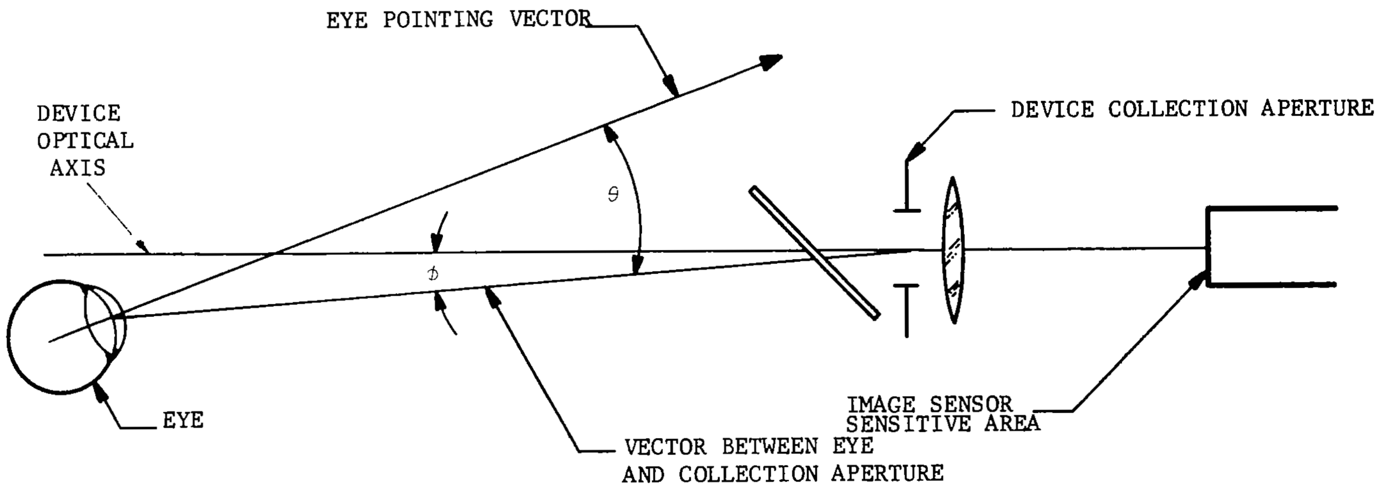


Figure 6 EYE DIRECTION MEASUREMENT WITH REMOTE OCULOMETER

Illumination Technique

The basic illumination technique for the remote Oculometer is the same as that used in the laboratory Oculometer. Namely, the eye is illuminated by an infrared source which subtends an angle of approximately one degree. By means of a beamsplitter, the aperture for the Oculometer collection lens is placed conjugate to the source position; the aperture also subtends approximately one degree. Due to the optical configuration of the eye, some of the radiation incident on it will pass onto the retina, as shown in Figure 7. The retina will reflect some of the incident radiation such that it passes out of the eye along the same paths as those by which the incident radiation entered the eye. The placement of the Oculometer collection aperture is such as to collect that reflected radiation. The image of the pupil on the image sensor is then bright relative to other eye features, as shown in Figure 5. A more complete discussion of the above technique is presented in "Interim Report, Laboratory Oculometer" by John Merchant, September 1968.

Optics of Remote Oculometer

Figure 8 presents a schematic of the basic optical system for the remote Oculometer. As can be seen in the figure, the illumination system consists of two lenses. Illumination lens No. 1 images the light source onto illumination lens No. 2. Illumination lens No. 2 images illumination lens No. 1 onto the eye space. Then the illumination aperture, which is located at lens No. 2, determines the angular size of the source seen by

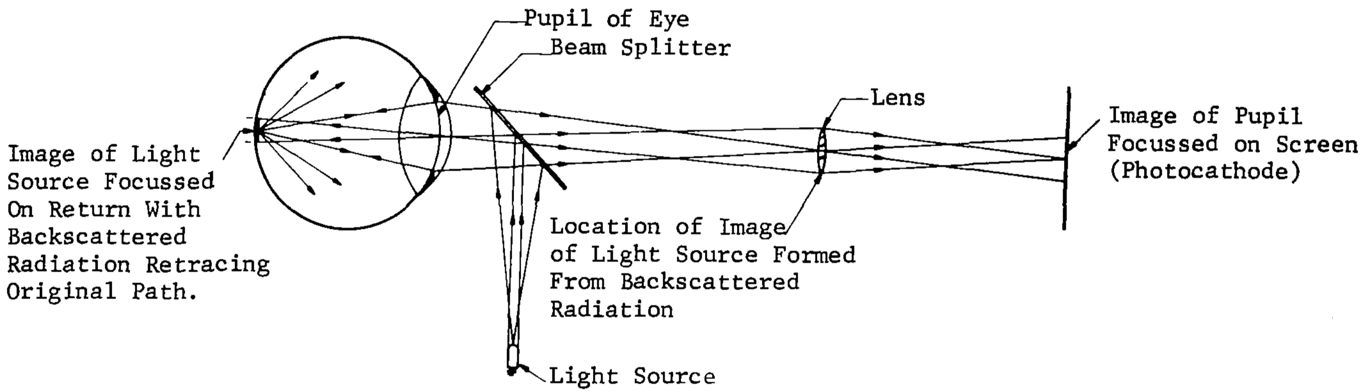


Figure 7 OCULOMETER ILLUMINATION TECHNIQUE

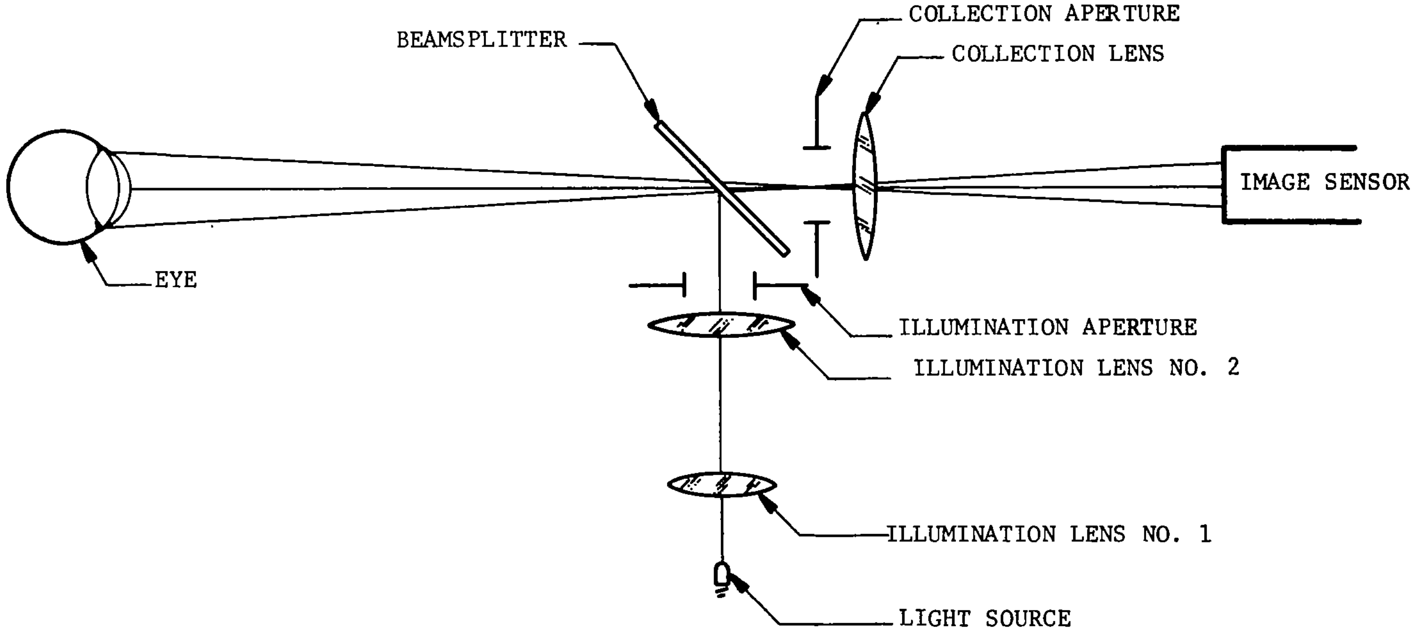


Figure 8 BASIC OPTICAL SYSTEM: REMOTE OCULOMETER

the subject. The effective area of lens No. 2 determines the size of the eye space that is illuminated. The reason for using this two-lens configuration is to make maximum use of the radiant power in the lamp (and thus have an efficient system), and to insure a reasonable uniformity of radiation of the eye space. In order to have a small illumination optical system, the focal length of lens No. 1 must be quite short.

The collection system consists basically of a lens (or lenses) which image the eye onto the image sensor. By use of a beamsplitter the limiting aperture of the collection system (collection aperture) is made to appear coincident with the illumination aperture as the subject views them. The basic variables in the design of the collection optics are the magnification (or demagnification) of the eye space, the distance between the collection aperture and the eye, and the distance between the collection aperture and the image sensor sensitive area. In a conventional optical system, the magnification is given by the ratio of the image distance to the object distance. In the remote Oculometer the object distance will be effectively fixed by the requirements for the use of the device. Then the magnification and the image distance are linearly related. The minimum usable magnification is determined by the maximum resolution of the image sensor that is used in the device. Namely, as the eye image is demagnified the effects of sensor resolution become more significant in determining the overall device accuracy. Thus, with conventional optics the image distance is fixed by the object distance and the minimum allowable magnification. However, it is desirable that the image distance be a minimum in order that the device size be small. One approach that can be used to reduce the aperture-to-photocathode distance is to use a telephoto design for the collection optics. In that case the back focal length of the optics is small and consequently a significant saving in device size can be obtained.

OPTOMECHANICAL DESIGN OF BREADBOARD REMOTE OCULOMETER

General Layout

The breadboard remote Oculometer is sketched in Figure 9 and a photograph of it is shown in Figure 2. The basic components of the device are laid out roughly to scale in Figure 10. These components are described below.

The image dissector and coils are the same as those used in the laboratory Oculometer. Namely, the image dissector is an ITT F4011 tube with an S1 photocathode and a 1.5-inch diameter photocathode. Only the central one-inch diameter area of the photocathode is utilized in this device, however. Namely, the 1.2 inch diameter eye space is imaged onto the photocathode with a 5:6 magnification, yielding a one-inch diameter image.

The collection optical system consists of positive lens L_2 and negative lens L_1. These are described in more detail under OPTICS p.18.

The illumination optical system consists of lenses L_3 and L_4. They are described in more detail under OPTICS.

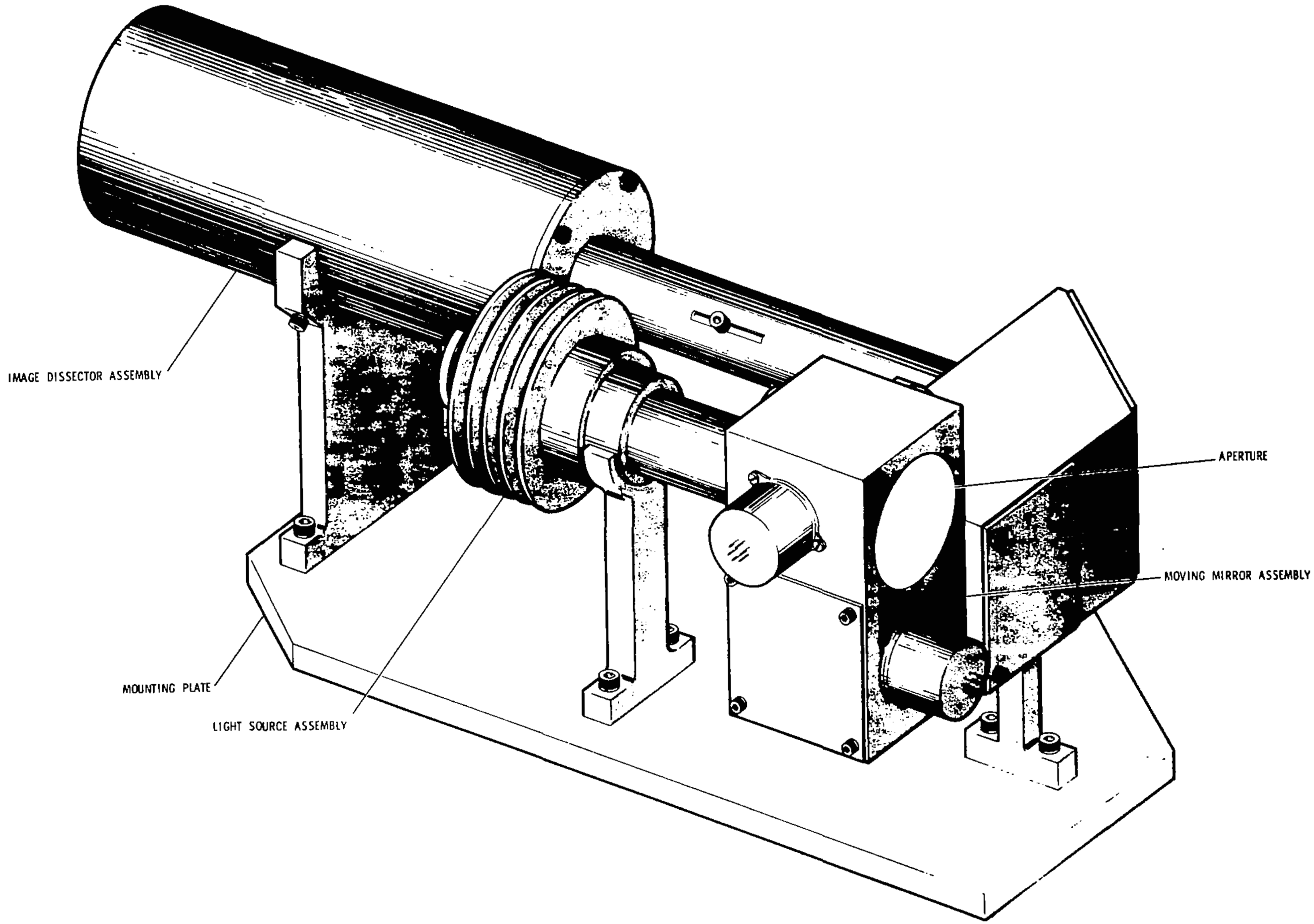


Figure 9 BREADBOARD REMOTE OCULOMETER OPTO-MECHANICAL UNIT

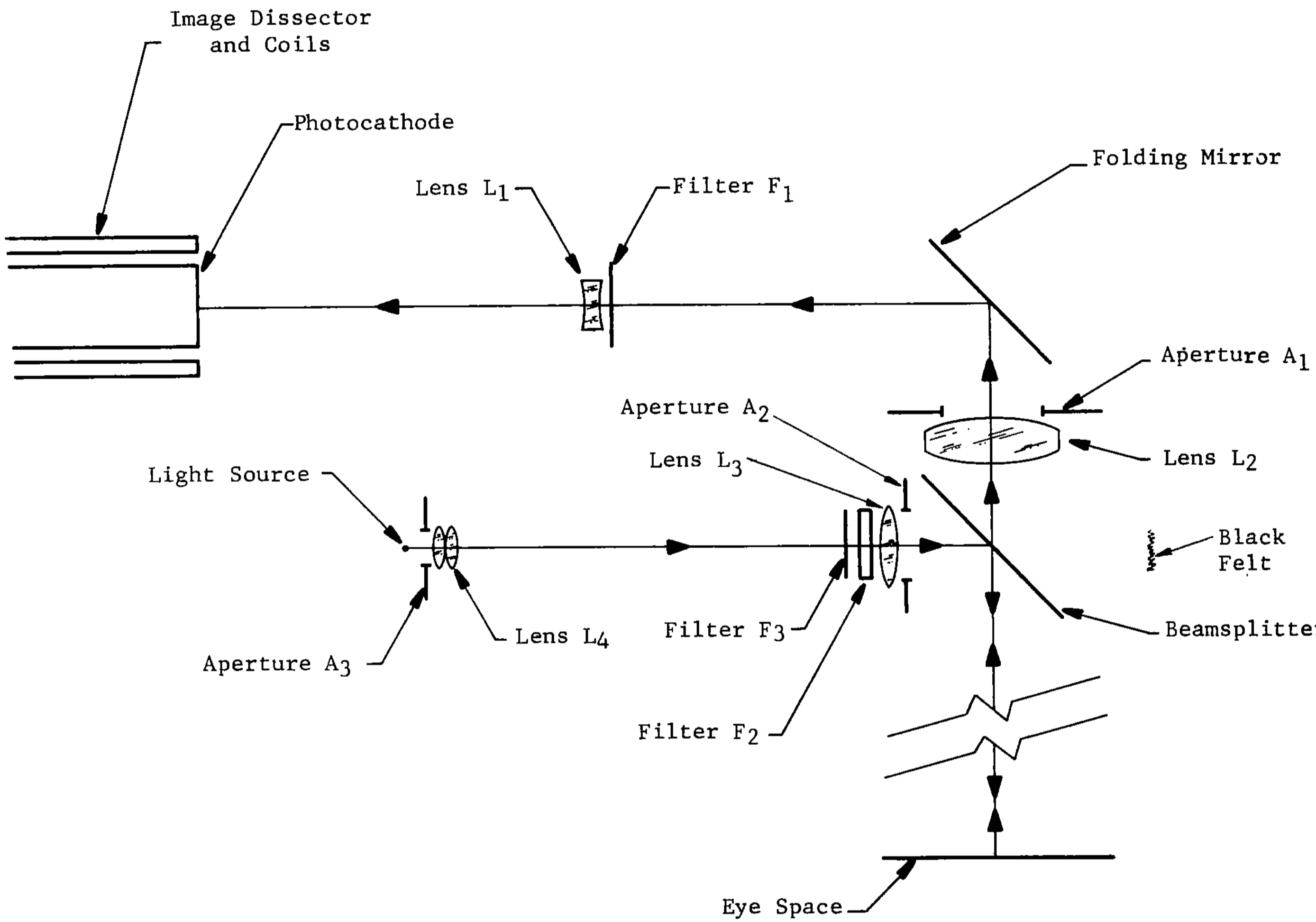


Figure 10 REMOTE OCULOMETER OPTICAL SYSTEM

The system has three basic apertures. Aperture A_1 is the collection aperture; it subtends approximately 1 degree with respect to the subject. Aperture A_2 is the illumination aperture; it determines the angular size of the light source to the subject (also approximately 1 degree). Aperture A_3, located at Lens L_4, determines the size of the eye space coverage; in this case the coverage is somewhat greater than 1.2 inches in diameter.

Three filters are used in the system. Filter F_1 is a No. 87 Kodak wratten filter which prevents visible and ultraviolet radiation from reaching the image dissector. Filters F_2 and F_3 are placed in the illumination system. Filter F_2 is also a No. 87 Kodak wratten and it prevents visible radiation from reaching the eye space. Filter F_3 is a Corning No. 7-69 absorbing filter; it prevents infrared radiation above one micron from reaching the eye space.

The beamsplitter is of the interference film type (Edmund Scientific catalog number 578). It nominally (in the visible) reflects 1/3 of the incident radiation at an incident angle of 45 degrees, but in the near infrared the reflection factor is closer to 1/6.

The light source is a GE No. 1962 tungsten filament lamp. It has a coil filament that is approximately 0.1 inch square. At 50 watt power dissipation it has the brightness of a 3200°K blackbody. In order to prevent excessive heating in the vicinity of the lamp, its housing is finned as is shown in Figure 9.

Figure 10 shows a strip of black felt near the other side of the beamsplitter from the illumination aperture. The function of this felt is to prevent undesirable reflection of source illumination into the collection optics. Namely, radiation that is initially transmitted by the beamsplitter impinges on the felt and is absorbed rather than being reflected back into other portions of the optical system.

A representation of the moving mirror system is shown in Figure 11. Two separate mirrors are used, one for pitch and one for yaw. The mirror sizes were determined by consideration of the size of the collection and illumination apertures and by the maximum mirror rotation angles involved; each mirror is 3.0 inches by 2.375 inches. Each mirror was gold coated to maximize reflection in the 0.85 to 0.95 micron region. The mirror flatness specification was 5 waves per inch.

OPTICS

Illumination Optics

The function of the illumination optics is to provide uniform illumination of the 1.2-inch diameter eye space with an effective 1-degree diameter source.

Figure 12 presents a ray trace of the illumination system. The lens L_3 (Jaegers No. 10E512) is an arhromat with 5.7-inch focal length and approximately 1.2-inch diameter. Lens L_4 (Jaegers No. 3C1208) consists of two adjacent doublets; the net

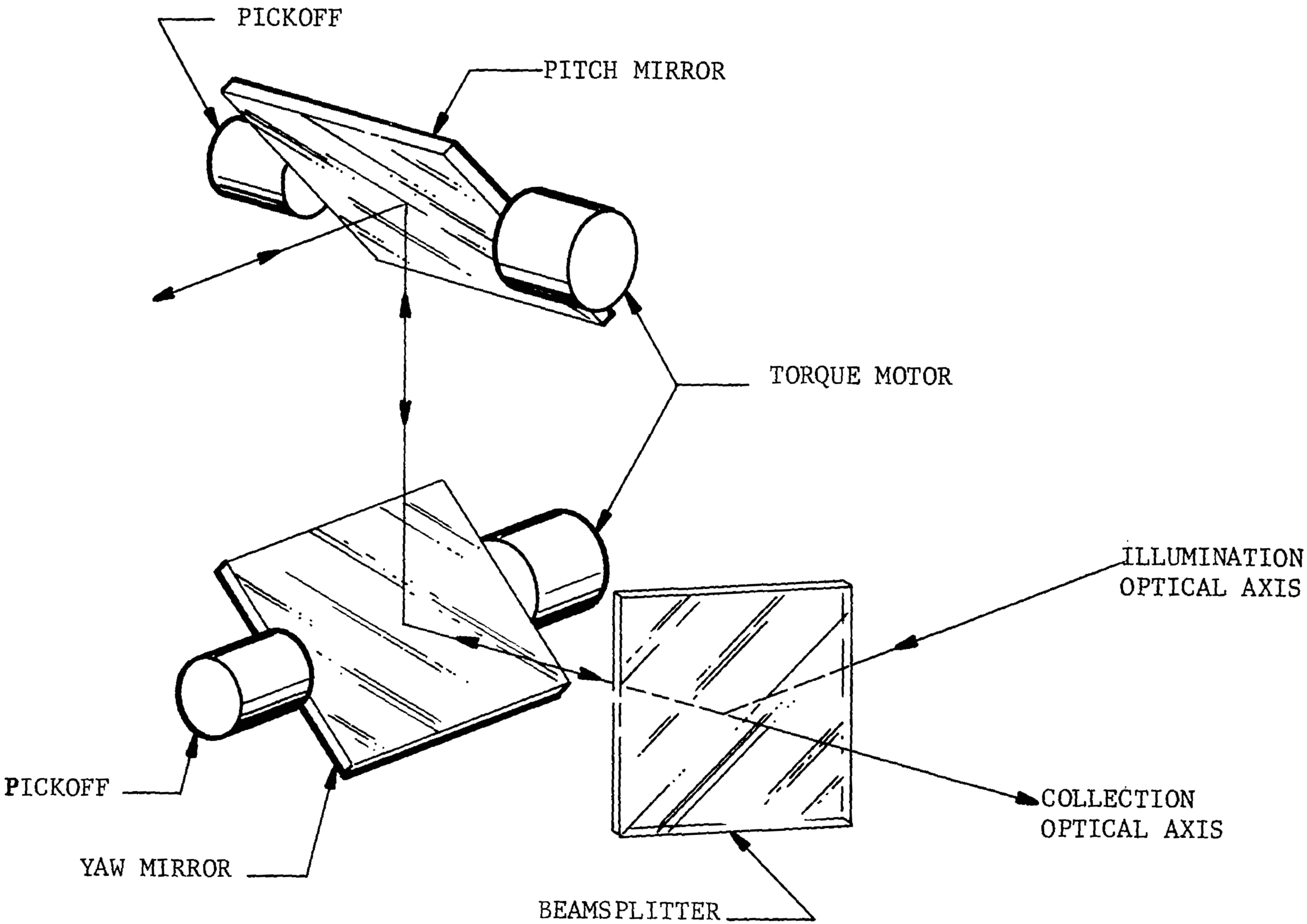
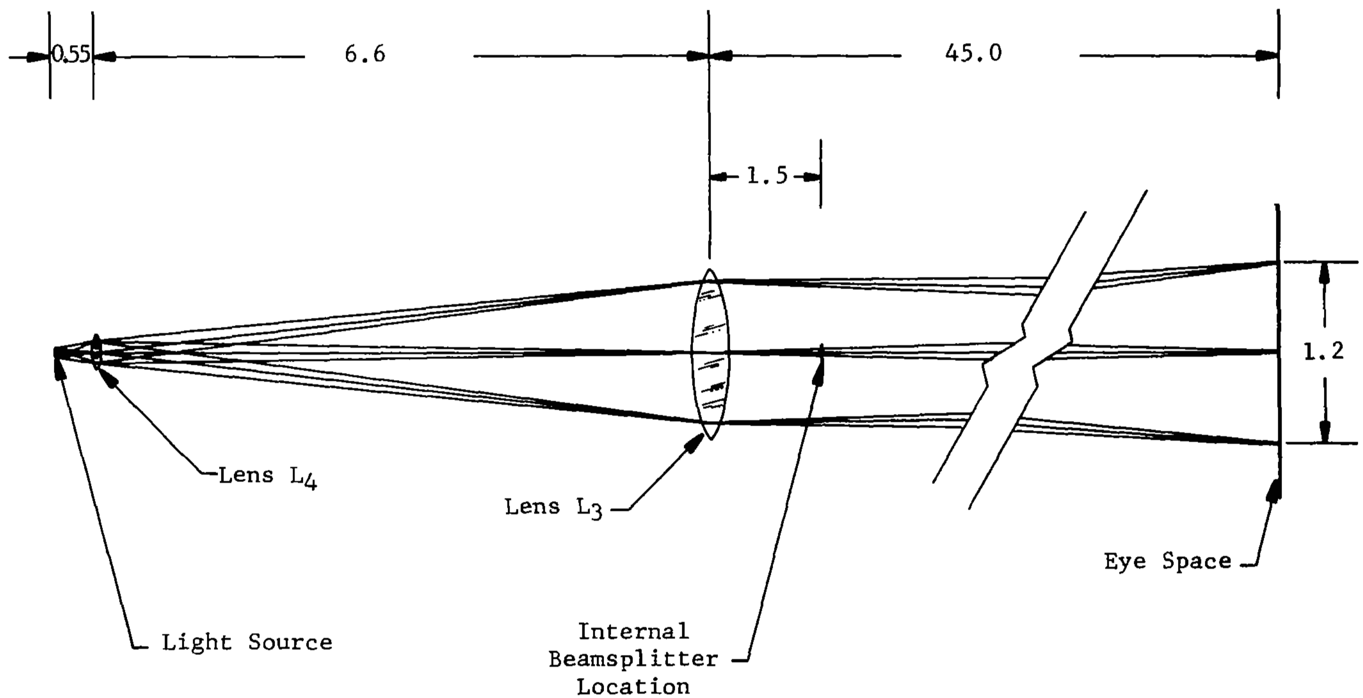


Figure 11 REPRESENTATION OF MOVING MIRROR LAYOUT



Note: 1) All dimensions in inches
2) Vertical Scale 1X
3) Horizontal Scale 1/2X

Figure 12 ILLUMINATION OPTICS

focal length is 0.5 inch and the effective diameter 0.4 inch.

Lens L_4 images the light source onto lens L_3 with a magnification of approximately twelve. Lens L_3 images lens L_4 onto the eye space with a magnification of approximately seven. The optical path distance between lens L_3 and the eye space is 45 inches.

Prior to device fabrication, this optical system was tested on the optical bench. It was found that it yielded better than ± 10% uniformity of illumination in the eye space. Also, visual inspection of the source image in lens L_4 indicated satisfactory performance.

Collection Optics

The function of the collection optics is to image the eye space onto the tube photocathode with a 5:6 magnification, and perform this imaging with less than 1% distortion and with less than a 5 mil blur circle.

Figure 13 presents a ray trace of the collection optics. Lens L_1 (Edmund Scientific No. 30448) is a doublet negative lens with a 1.93-inch focal length and 3/4-inch diameter. Lens L_2 (Edmund Scientific No. 5117) is an achromatic doublet with 7.71-inch focal length and 2-inch diameter (only the central one-inch diameter is utilized, however). The collection system is then of telephoto construction and is significantly smaller than could be obtained with a more conventional design. Speci-

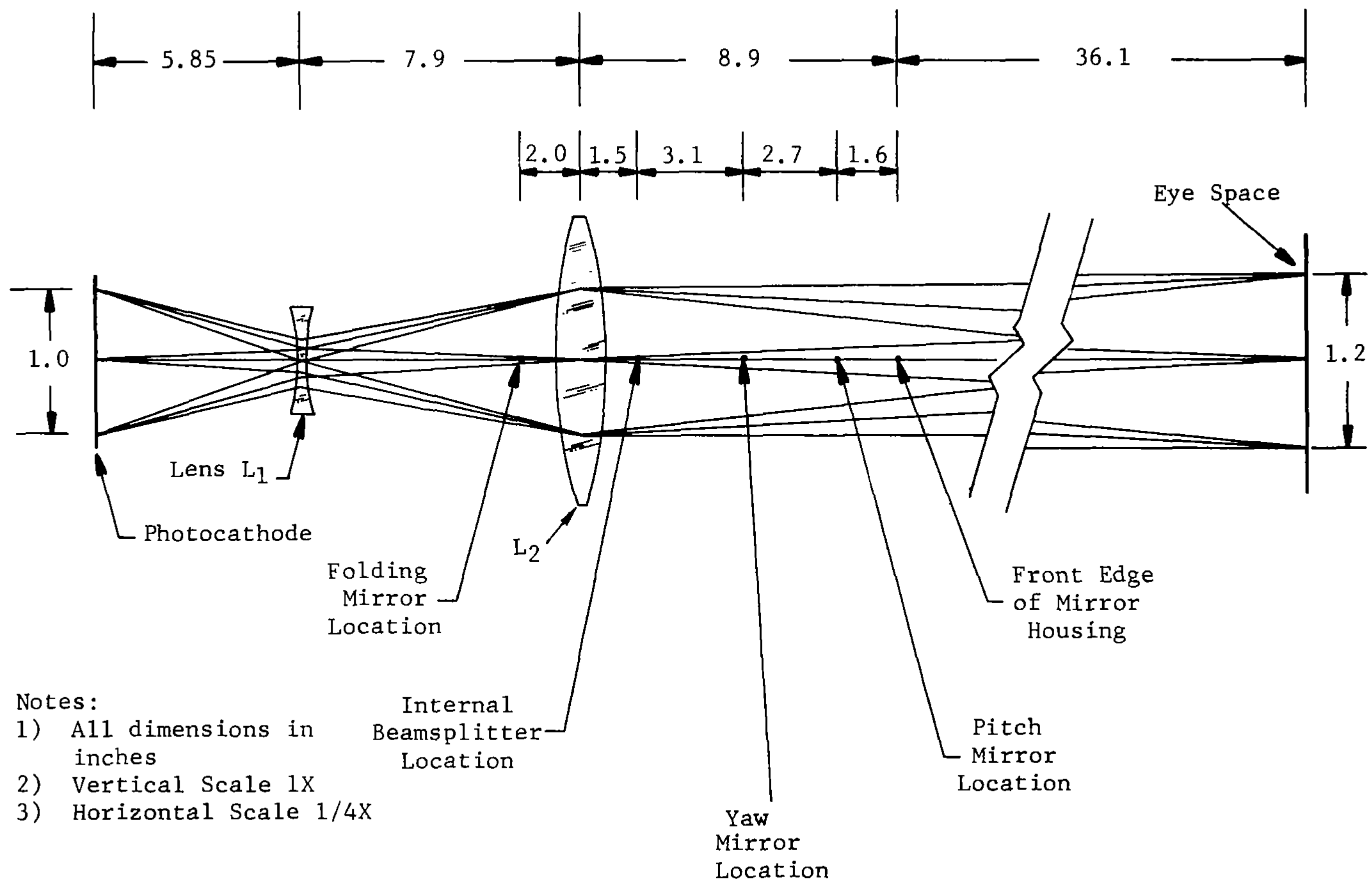


Figure 13 COLLECTION OPTICS

fically, the distance from photocathode to lens L_2 is 13.8 inches while distance from L_2 to the eye space is 45 inches.

Figure 13 also shows the locations of the yaw and pitch mirrors along the optical axis. Due to the space requirements for these mirrors, the optical path distance between the lens L_2 and the edge of the mirror housing is approximately 8.9 inches. Then the distance between the mirror housing and the eye space is approximately 36 inches. It should be noted that there is some axial position adjustment provision for the negative lens; this allows some adjustment of the position of eye space relative to the device.

This optical system was also tested on an optical bench prior to device fabrication. Photographs of the image plane were taken when the object was a bar chart and when it was a resolution target. Subsequent examination of the photographs indicated that the distortion is less than 1% over the desired image field, and the maximum blur circle is less than 5 mils.

MOVING MIRROR SYSTEM

General

The function of the two-axis moving mirror system is to deploy the 1.2-inch diameter instantaneous field of view of the Oculometer optics over a specified 5 inch by 5 inch area in response to eye displacements in that area; this is illustrated in Figure 14. Thereby the subject's allowable lateral head movement

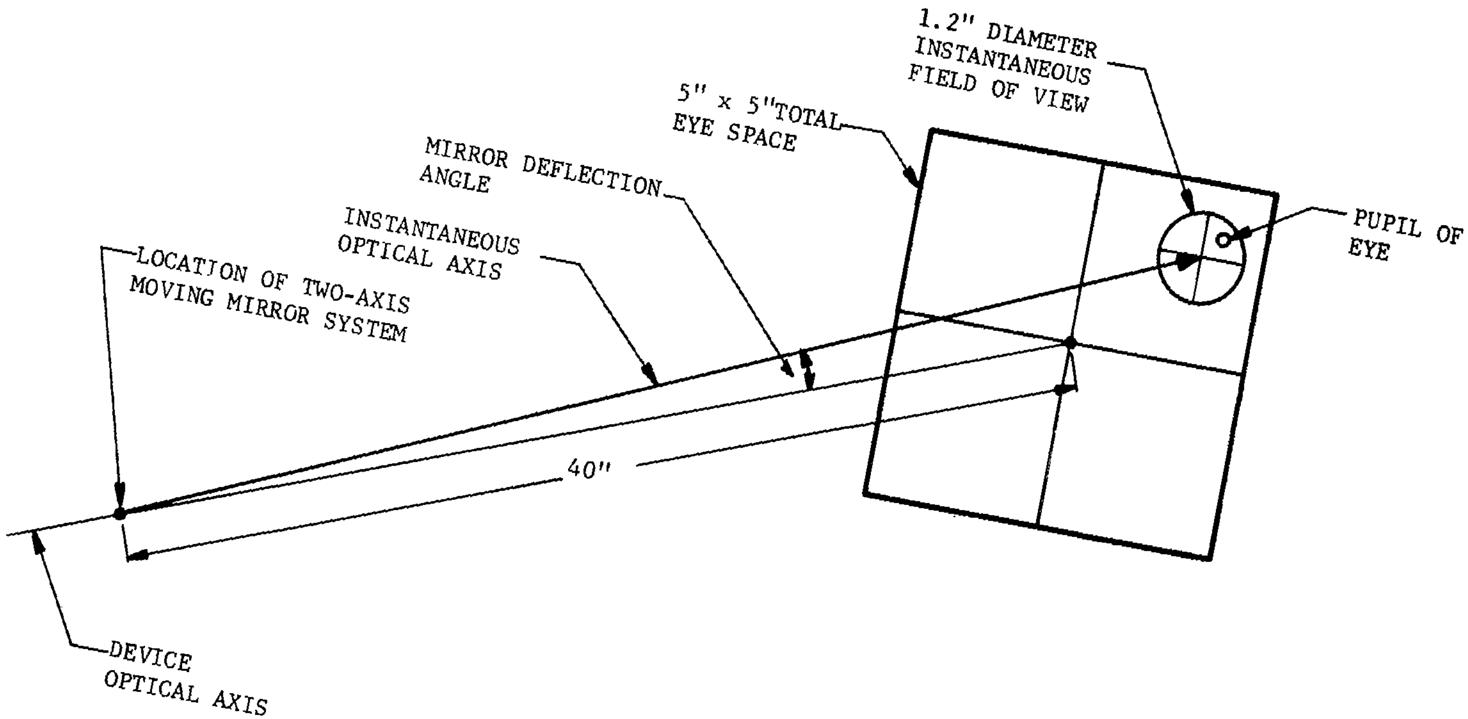


Figure 14 REMOTE OCULOMETER FIELDS OF VIEW

range is substantially increased.

As described under OPTICS and illustrated in Figure 11, the mirror system consists of two mirrors which rotate about axes orthogonal to one another. The Oculometer itself provides output signals defining the eye position (X_1, Y_1) relative to the center of the image sensor photocathode. The coordinates (X_2, Y_2) of the center of the photocathode are uniquely defined by the deflections of the mirrors. Let (X_3, Y_3) be the coordinates of the eye relative to the center of the 5 inch by 5 inch specified eye space. Then,

$$X_3 = X_2 + Y_1$$

$$Y_3 = Y_2 + Y_1$$

As is discussed in the following sections, the eye position information from the Oculometer controls the mirror rotations so that the eye tends to be centered in the instantaneous field of view of the Oculometer as it moves throughout the specified 5 inch x 5 inch eye space. Because the mirror rotation angles are small, it can be assumed that the mirror system will provide independent control of X_2 and Y_2 from the input control signals without the necessity of any axis transformations.

The performance of the mirror system is determined basically by the following two operational requirements.

1) The maximum dynamic tracking error (namely, X_1, Y_1) should be less than 0.40 inch. This insures that the eye is always held within the instantaneous field of the tracking system.

2) The system should allow eye tracking under the maximum head motion rates likely to occur in the planned use of the device.

Mirror Dynamics

The mirror control system consists basically of dc torque motors to rotate each mirror, infinite resolution magnetic pick-offs to provide rate feedback for the system, and the Oculometer pupil position outputs to provide appropriate error information. The differential equation of motion is then given as follows:

$$I\ddot{\theta}_2 + h\dot{\theta}_2 + k\ (2\theta_2 - \theta_3) = 0 \qquad (1)$$

where,

I = moment of inertia of mirror
h = rate feedback scale factor
k = loop gain scale factor
θ_2 = mirror rotation angle relative to a null angle
θ_3 = angular position of pupil centroid relative to a null angle

The control system diagram corresponding to the above equation is shown in Figure 15.

Equation (1) may be alternatively written,

$$I\ddot{\theta}_2 + h\dot{\theta}_2 + 2k\theta_2 = k\theta_3 \tag{2}$$

Or, in transform notation,

$$\theta_2 = \frac{k\theta_3}{Ip^2 + hp + 2k}$$

$$\theta_2 = \frac{w_o^2 \left(\frac{\theta_3}{2}\right)}{p^2 + 2\zeta p w_o + w_o^2}$$

where $w_o^2 = 2\ k/I$

$$\zeta = \frac{1}{2w_o} (h/I)$$

The dynamic tracking error $\Delta\theta$ is given as follows.

$$\Delta\theta = \theta_3 - 2\theta_2$$

$$\Delta\theta = \frac{\theta_3 (p^2 + 2\zeta p w_o)}{p^2 + 2\zeta p w_o + w_o^2}$$

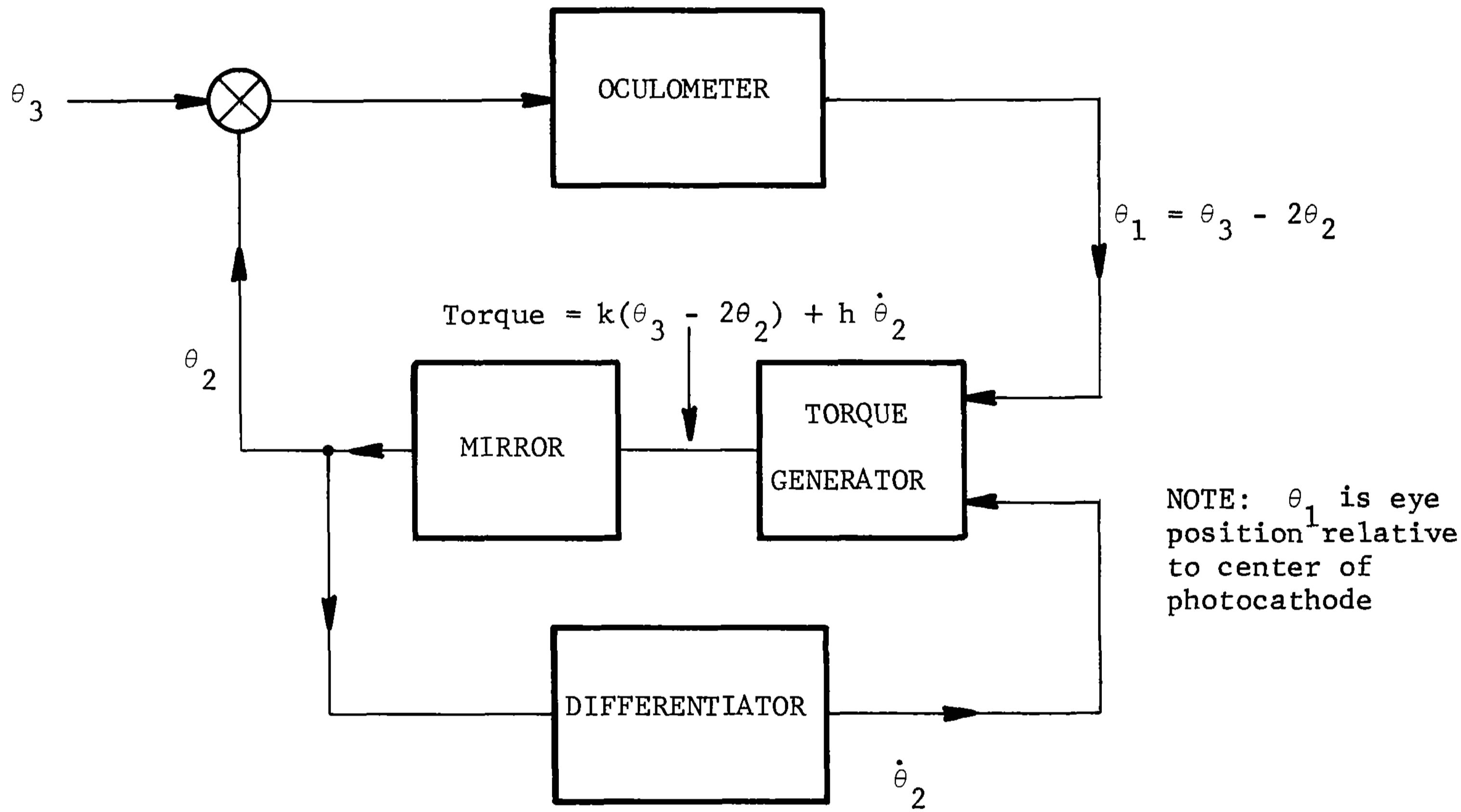


Figure 15 EQUIVALENT BLOCK DIAGRAM OF MIRROR TRACKING SYSTEM

Now assume that θ_3 varies sinusoidally with amplitude A and angular frequency Ω.

$$\theta_3 = A \sin \Omega t$$

Then,

$$\Delta\theta = \frac{A\,(2j\zeta w_o \Omega - \Omega^2)}{-\Omega^2 + 2\zeta w_o \Omega j + w_o^2}$$

Now let $x = \Omega / w_o$

Then $$\Delta\theta = \frac{A\,(-x^2 + 2j\zeta x)}{1 - x^2 + 2j\zeta x}$$

Then $$|\Delta\theta| = \frac{Ax\,(x^2 + 4\zeta^2)^{1/2}}{[(1-x^2)^2 + 4\zeta^2 x^2]^{1/2}}$$

For the optimum dynamic response, $\zeta = 1/\sqrt{2}$

Then $$|\Delta\theta| = \frac{Ax\sqrt{2 + x^2}}{\sqrt{1 + x^4}}$$

For small values of x,

$$|\Delta\theta| \doteq A\sqrt{2}\,x$$

$$|\Delta\theta| \doteq \frac{A\sqrt{2}\,\Omega}{w_o}$$

Alternatively,

$$w_o = \frac{A\sqrt{2}\ \Omega}{|\Delta\theta|} \qquad (3)$$

The relevant system parameters can then be determined from the following operational requirements.

Table I Operational Requirements

Coverage of Eye Space	± 2.5 inches
Range of Eye	40 inches
Angular Deflection of Beam	± 3.8 degrees max
Angular Deflection of Mirror	± 1.9 degrees max
Maximum Tracking Error	0.40 inch or 0.6 degree
Maximum Head Velocity	10 inches/s or 15.2 degrees/s
Maximum Head Acceleration	Equivalent to a displacement of ± 2.5 inches at one Hz

The value of w_o may then be determined from equation (3) above.

$$w_o = \frac{(3.8)\sqrt{2}\ (2\pi)}{0.60}$$

$$w_o = 12.6\sqrt{2}\ \pi \text{ radians/s}$$

The loop gain scale factor is given as follows:

$$k = \frac{I\, w_o^2}{2}$$

Calculations determine that the mirror's moment of inertia is approximately $1.8 \cdot 10^{-2}$ oz - in. $\cdot\ s^2$.

Then,

$$k = \frac{(1.8) \cdot 10^{-2}}{2} (160)(2)\pi^2$$

$$K = 29 \text{ oz in./radian}$$

Similarly, the rate feedback scale factor is determined as follows:

$$h = 2\zeta\, w_o\, I$$

$$h = 2\left(\frac{1}{\sqrt{2}}\right) (12.6\sqrt{2}\,\pi)\ (1.8 \cdot 10^{-2})$$

$$h = 1.4 \text{ oz-in.-s/radian}$$

The Oculometer pupil position output scale factor is 10 volts per inch, or 400 volts per radian. The torque motor (Aeroflex TQ10W) sensitivity is 7.6 oz-in./A. Thus the motor drive amplifier should have a net gain of approximately 10^{-2} amps out per volt input.

The angular pick-off device (Shaevitz R3B Rotary Variable Differential Transformer) yields an ac signal whose output sensitivity is proportional to the driving voltage amplitude. The demodulated output sensitivity, with the associated circuitry described in the next section, is 1.5 volts dc per degree. The output is then differentiated with a time constant τ. The output of the differentiator is 1.5 τ volts per degree per second. The scale factor of the corresponding driving amplifier should then be $0.0022/\tau$ amps per volt.

The maximum torque requirement (T_m) for the torque motor is given by the following expression.

$$T_m = \text{maximum} [I\ddot{\theta}_2]$$

$$T_m \doteq \frac{A \ \Omega^2}{2} \ I$$

$$T_m \doteq \frac{(3.8) \ (2\pi)^2}{2 \ (57)} \ (1.8 \cdot 10^{-2})$$

$$T_m = 2.4 \cdot 10^{-2} \text{ oz-in.}$$

Mirror Control System Electronics

Figure 16 presents a general block diagram of the mirror control electronics. As is indicated there, the system has three modes of operation, corresponding to the three positions of the switches in the diagram. These modes of operation are described below.

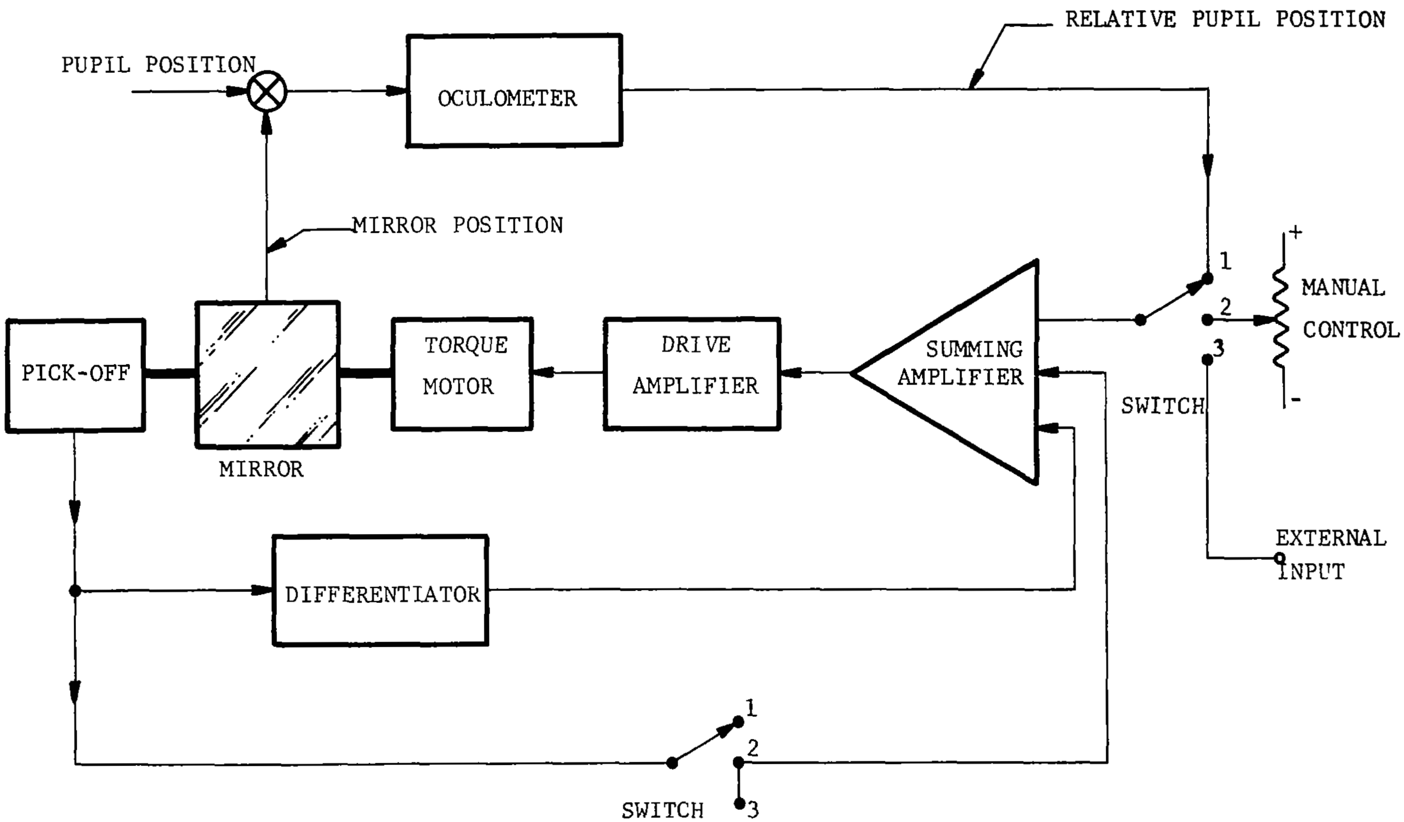


Figure 16 EQUIVALENT BLOCK DIAGRAM: MIRROR CONTROL ELECTRONICS

Mode 1: This is the tracking mode that is described in the previous section. Here it is assumed that the Oculometer image dissector is scanning the pupil of the eye. The mirror motion is then controlled by the Oculometer pupil position signal and the mirror rate signal derived from the mirror pick-off.

Mode 2: This is a manual control mode. Namely, the experimenter can control the mirror position by manual control of a potentiometer.

Mode 3: This mode allows mirror position control by a signal external to the Oculometer. For example, application of a step voltage, in this mode, can allow evaluation of the system's step response.

Figure 17 presents a more detailed block diagram of the electronic system. The various blocks of the system are described below.

First consider the mirror pick-off, which is a Shaevitz R3B Rotary Variable Differential Transformer (RVDT). Rotation of the mirror shaft varies the effective transformer coupling. The transformer output amplitude and phase are then functions of the voltage input and the shaft rotation angle. The transformer input voltage is a 2 kHz sine wave of 26 volt peak to peak amplitude. This sine wave is obtained by appropriate filtering (low pass filter No. 1) of the 2 kHz square wave in the original Oculometer electronics.

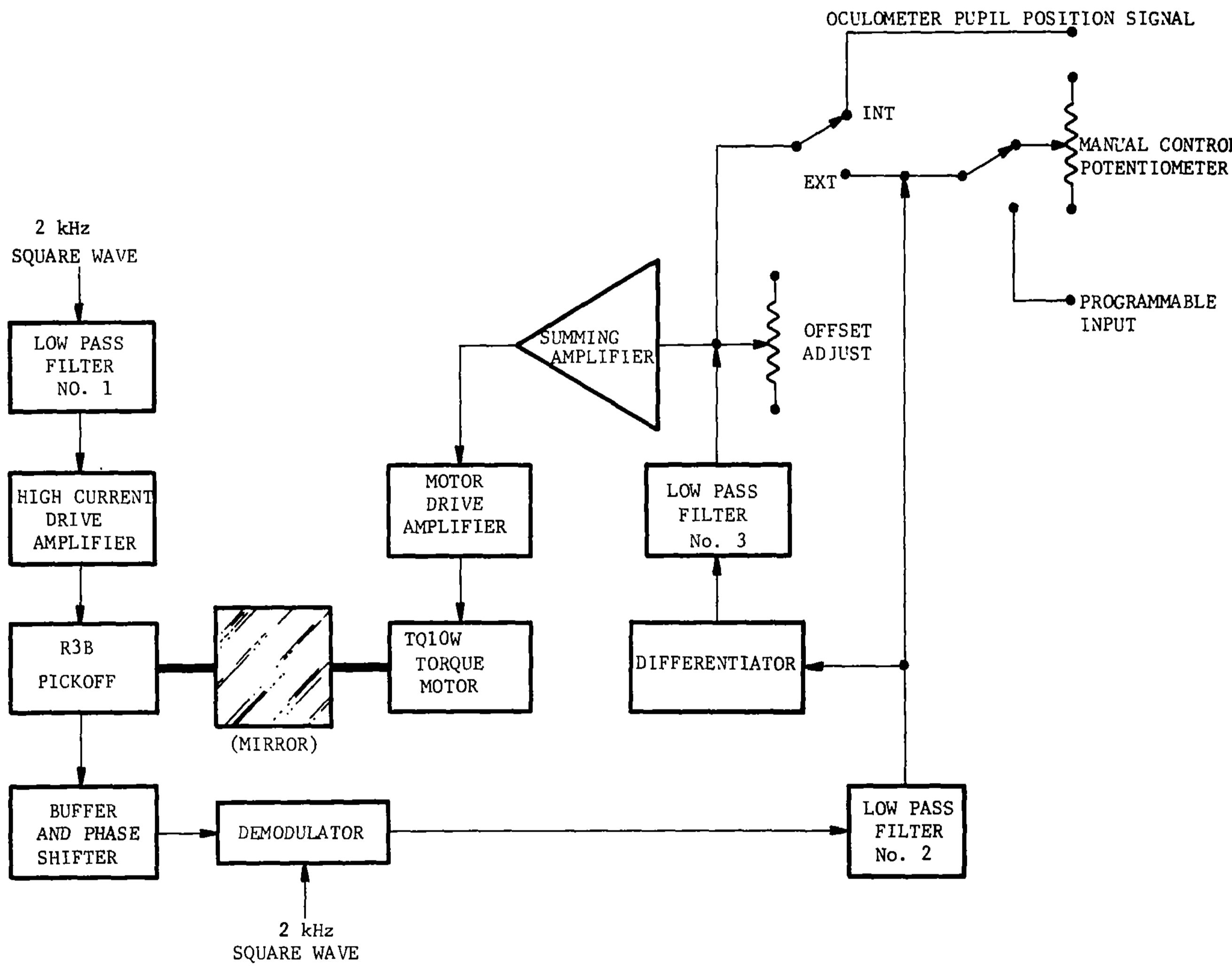


Figure 17 DETAILED ELECTRONIC BLOCK DIAGRAM: MIRROR CONTROL ELECTRONICS

A high current amplifier is used to provide the RVDT with the proper signal amplitude. The transformer configuration is such that the output signal gives a sensitivity of 50 mV peak to peak per degree of shaft rotation. This output signal is not in proper phase with the nominal demodulation signal; specifically, the low pass filter No. 1 and the transformer have introduced a phase shift with respect to the original 2 kHz square wave. The output signal is then fed to an amplifier that serves as a buffer and introduces an 11 degree phase lag, thus restoring the proper phase. The restored output signal is then fed to the demodulator which effectively full wave rectifies its input; the sign of the demodulator output corresponds to the sign of the mirror rotation angle. The drive signal for the demodulator is a 4 kHz square wave (taken from the Oculometer electronics) which drives a flip-flop, thereby providing two 2 kHz square waves which perform the actual demodulation. The demodulated signal is then fed to low pass filter No. 2 which effectively removes the 2 kHz content of the signal. The signal scale factor at this point is then 1.5 volts dc per degree of shaft rotation. The smoothed demodulated signal is then differentiated; the differentiator time constant is 13 milliseconds and its output sensitivity is thus approximately 20 mV per degree per second. Low pass filter No. 3 then further attenuates high frequency spikes in the differentiated signal.

Next, consider the components that drive the torque motor. The various control signals are fed to a summing amplifier, which is an operational amplifier in the summing mode. The output of the summing amplifier then enters a high current unity gain amplifier that supplies the power for the torque motor. The load resistance in the torque motor is 175 ohms; its sensitivity is 7.6 oz-in. of torque per ampere of input.

Some of the relevant scale factors for the above electronic system are listed below.

1) The pupil position input to the control electronics has a scale factor of 10 volts per inch or 15 volts per degree of eye displacement.

2) The pupil position sensitivity at the torque motor input is 7.5 volts per degree or 0.045 amp per degree.

3) The loop gain scale factor is 20 oz-in. per radian.

4) The rate feedback scale factor at the motor input is 0.0018 amps per degree per s; this is equivalent to 0.8 oz-in.-s/radian. This scale factor is then close to that for optimum response damping.

The motor control electronics is contained in two boxes as shown in Figure 3. One box contains a ±15 volt power supply. The other box contains two circuit cards, one for the yaw control mirror and the other for the pitch control mirror. The cards for the yaw control mirror and that for the pitch control mirror are identical except for the following two items:

1) Low Pass Filter No. 1 (see Figure 17) is on the yaw card but <u>not</u> on the pitch card; namely, one low pass filter serves

both channels (yaw and pitch).

2) The demodulator flip-flop is on the pitch card only; its output is fed to both channels, however.

One comment can be made concerning the final determination of the electronic system parameters. In the initial system testing the loop gain was set approximately a factor of five higher than the above analysis indicates (so as to yield tighter eye tracking). The system would then lose track of the eye after a blink. Specifically, during the blink the pupil search raster in the Oculometer was causing the mirror to move away from the eye, and the eye could not be found quickly after the blink. When the loop gain was lowered to the present value, the effects of the pupil raster were reduced and the proper system recovery after a blink was observed. The above raster effects can be eliminated entirely by always preventing the raster signals from reaching the mirror control electronics.

The total system block diagram is shown in Figure 18. Specifically, this includes the original Oculometer electronics, and the mirror control electronics.

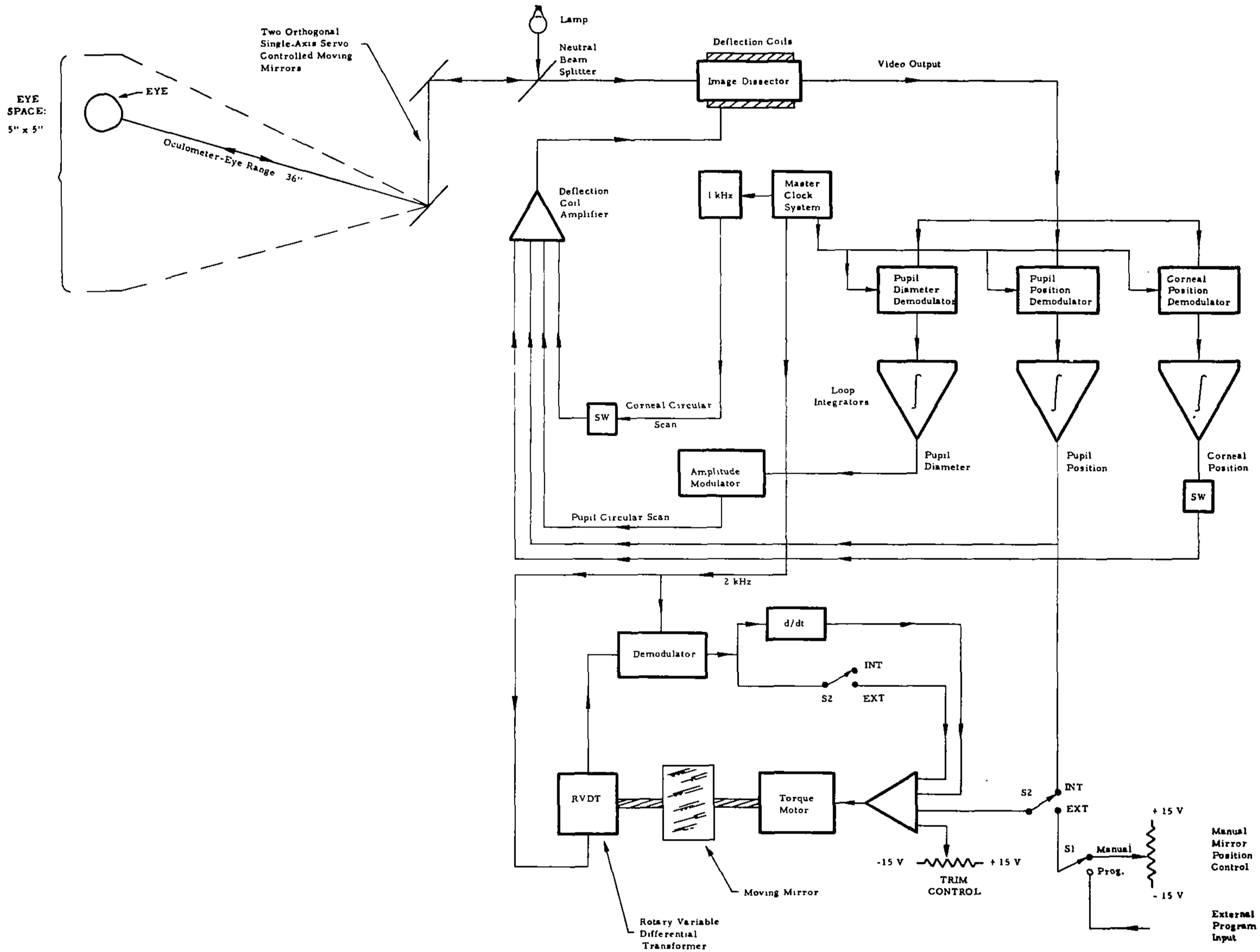


Figure 18 TOTAL SYSTEM BLOCK DIAGRAM

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