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DESIGN AND CONSTRUCTION OF A PORTABLE OCULOMETER FOR USE IN TRANSPORTATION ORIENTED HUMAN FACTORS STUDIES

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16. Abstract

This report describes development of an instrument designed to acquire and process information about human visual performance. The instrument has the following features: (1) It can be operated in a variety of transportation environments including simulators, cars, trucks, trains, and air traffic control stations; (2) The visual performance measurements are made without alteration of the subject's normal visual behavior; and (3) The data can be presented to the experimenter as either a video picture of the scene with the fixation point superimposed, or as derived eye-motion parameters.

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INTRODUCTION

One important aspect in the development of safer and more efficient transportation systems is consideration of the human factors problems related to the operator's ability to acquire, process, and apply information. As the complexity of the systems increases, the man/machine interactions become correspondingly more complex, and it becomes increasingly important to have practical techniques for accurately and objectively assessing both normal and degraded human performance.

During the past few decades, a great deal of effort has been put into establishing human performance limitations, understanding human reactions to stress, and studying the many aspects of man-machine interaction. Impetus in this area was provided initially by the demands of military and civil aviation and more recently by requirements of NASA's manned space flight activities. It should be noted that most of the efforts in the past have been directed toward the study of well-trained, highly-motivated, cooperative individuals. Indeed, in many cases, the individual's survival directly depended upon the optimization of the human-engineering aspects of the system, so it is understandable that he would be very cooperative in allowing his performance to be studied. The more recent interest in the study of human factors relevant to ground transportation safety -- automobiles, trucks, urban and inter-urban trains -- has yielded a different class of problems. In general, the human operator now being considered has not had his physical abilities optimized through training and selection; his physiological and psychological condition is a highly variable unknown quantity, and, at least for the automobile driver, his level of training is often minimal. Quite often, efforts to modify and improve the systems are met with resistance or indifference (as evidenced by lack of seat belt usage) even when the factual basis for the modification is well-accepted.

Compounding these problems has been the lack of simple, reliable, non-invasive measurement techniques which are applicable to non-aerospace human factors studies. As has been indicated, subject variability coupled with an uncontrolled measurement environment imposes serious problems for the investigator. However, when the ultimate payoff for solution of the problems is considered, namely, significantly reducing the transportation-related injuries and fatalities while increasing the usefulness and efficiency of transportation systems, a vigorous effort to solve the problems is warranted.

In general, the physiological and psychological factors that are pertinant to transportation research can be catagorized as follows:

(1) Sensory mechanisms

(2) Motor skills performance,

(3) Emotional reactivity,

(4) Physical capabilities,

(5) Indices of general health,

(6) Reactions to stress,

(7) Physiological indices of psychological stress.

Studies of these factors are important for determining normal operator-performance capabilities as well as for understanding the effects and magnitude of performance decrements due to fatigue, alcohol, drugs, emotional stress, physical stress, etc.

As an initial step in the development of suitable techniques and instrumentation, work has started on a system for measuring a vehicle operator's visual performance and ocular motions without attachment or encumberance. This effort is considered important for two reasons: (1) The assessment and understanding of visual performance is basic to most human factors studies, since vision is a primary source of information to the operator, and since visual behavior is an extremely sensitive indicator of certain aspects of the operator's physiological state. (2) The development of techniques to measure visual performance characteristics has been hampered due to the lack of instrumentation capable of measuring eye-motions without encumbering the operator and subsequently altering his normal behavior patterns.

This report describes the development of such a system (the oculometer) by the staff at the Transportation Systems Center during the past year. Included are the theory of operation for the oculometer, the engineering details, preliminary evaluation of the system performance characteristics, and planned experiments.

THE PORTABLE OCULOMETER SYSTEM

This section outlines the basic theory of operation of the oculometer, the sensitivity calculations for determining safe illumination levels, and the design constraints for the instrument.

GENERAL

An oculometer is an electro-optical instrument developed to measure some of the basic characteristics of human eye-motions. These include the dynamic measurement of visual fixation points referenced to a pre-calibrated two-dimensional scene, the recording of visual fixation points referenced to a video recording of the observer's scene, measurement of involuntary eye-motions which serve as sensitive indicators of the subject's physiological state (including the dynamic measurement of pupil diameter) and use of eye motions as a control input (ocular joystick).

The oculometer is unique in that it is the only instrument capable of performing these measurements with no attachment to the subject's head, eye, or body, while retaining high accuracy and stability. Comparisons of critical parameters for other eye measurement techniques are contained in Appendix B.

Since the instrument's output is an electronic signal proportional to the direction in which the eye is looking, the eye position information can be displayed for direct observation by the experimenter or can be processed on or off-line by computer.

The oculometer principle was first demonstrated by Merchant in 1968 (Ref. 1). During this initial work, two versions of the instrument were developed to test the validity of the concept. First to be constructed was the laboratory, or "proximate", oculometer which was limited by a very short instrument-to-subject working distance. Next, a remote instrument was developed which demonstrated the feasibility of increasing the working distance to about 1 meter through suitable design of the optics (Ref. 2). Both instruments worked well enough to establish the feasibility of the concept and were useful in suggesting the steps to be taken to design and construct an instrument practical for use in human factors studies. To overcome some of the electronic processor limitations inherent to both of these instruments, a computer-controlled version of the system was built by the MIT Project MAC Artificial Intelligence Group (Ref. 3). For this system, the remote optical head was coupled to the MAC PDP-6 computer which generated the tracking and scanning signals. This system had the advantage of providing interaction between eye-motion signals and computer-generated displays, a technique useful for simulation experiments and for eye-control applications.

DESIGN CONSTRAINTS

Since some of the basic requirements for an oculometer useful to transportation studies are that it be portable, economical, and reliable, certain undesirable features of the original instruments had to be overcome. Specifically, these were:

(1) Marginal sensitivity due to the particular image sensor used (an image dissector tube)

(2) Lack of flexibility in selection and adjustment of instrument-to-head distance

(3) Unreliability in the electronics

(4) Bulkiness and high-power consumption by the electronic controller

(5) Operating restrictions due to the lack of automatic focusing.

In the present version of the instrument, all but one of these limitations have been overcome. One of the most significant advances has involved the use of a silicon-matrix vidicon-tube as the image sensor. Use of this tube has resulted in improving system sensitivity (due to higher quantum efficiencies in the infrared), reducing the electronic complexity (standard TV-raster scanning techniques are used), and significantly reducing the overall system cost.

The general design philosophy for the oculometer was to develop a field portable instrument that could be used for visual performance measurements in the laboratory, in vehicle simulators, and in operating vehicles.

BASIC PRINCIPLES OF OPERATION

The TSC portable oculometer is composed of two major subsystems: the electro-optical head and the electronic controller. The operating principles of the oculometer are as follows. The eye of the subject is illuminated by a collimated infrared light source located in the optical head (Figure 1). An infrared-sensitive video camera, also located in the optical head, detects the reflected light from the eye and transmits a video image of the eye to the electronic controller (Figure 2A). The image contains two important features

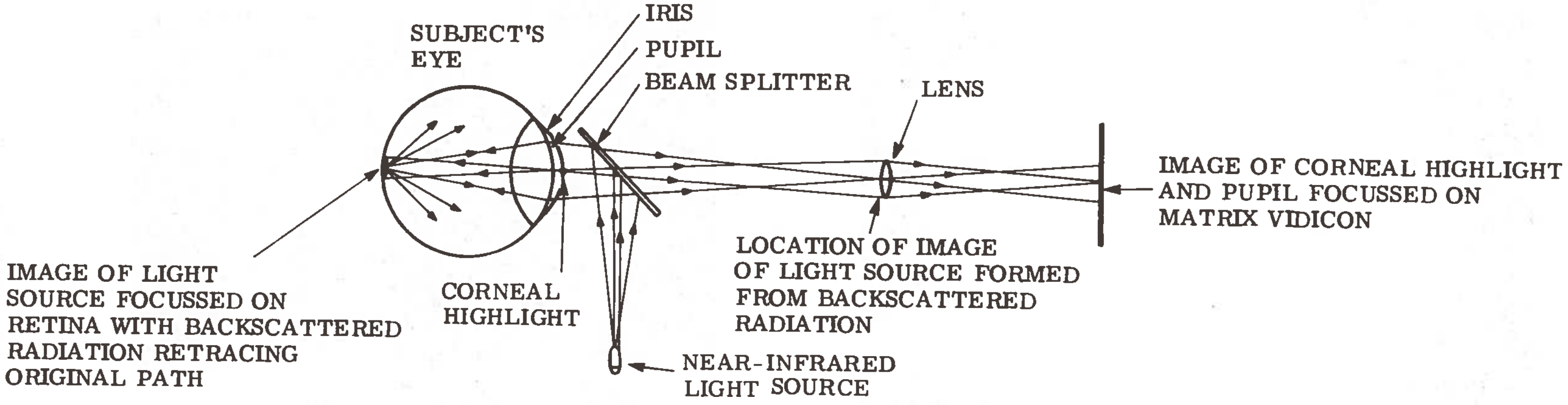
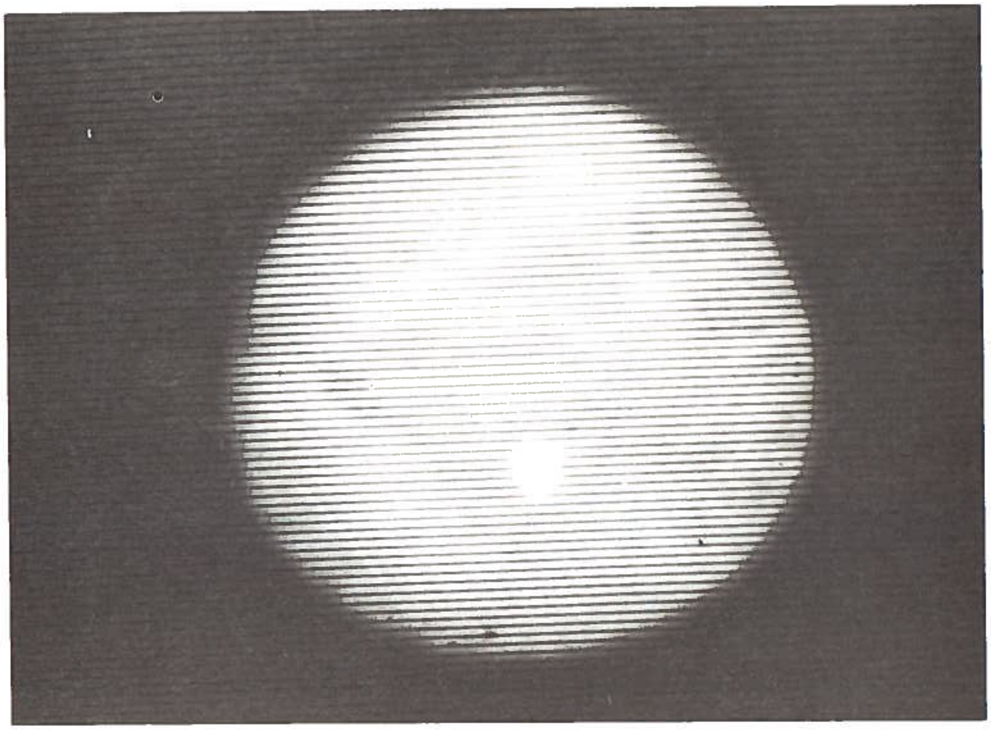
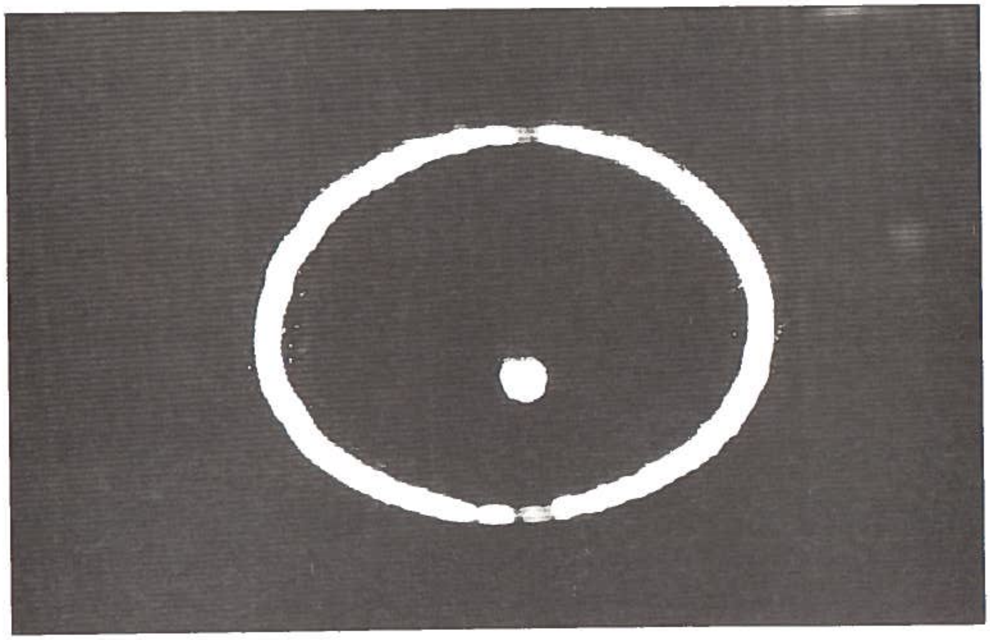


Figure 1. Illumination Principle



A. Video Image



B. After Threshold Detection

Figure 2. Photograph of Eye Image

(Figure 3): (1) The image of the bright pupil formed by light scattered from the retina and re-emerging through the lens; and (2) the reflection of the illumination source (a point source) from the corneal-air interface. From the geometry of Figure 4, it is apparent that the eye pointing direction will be proportional to a vector connecting the centroid of the corneal highlight to the centroid of the pupil. Moreover, to a first approximation, this vector will be independent of head motions (Ref. 4).

Upon receipt of the video signal of the eye image, the controller employs video processing circuitry to detect the pupil-iris boundary and the corneal highlight (Figure 2B). These signals are then used for calculation of the pupil and corneal centroids and the resultant corneal-pupil position vector. This vector is available to the experimenter as a voltage proportional to the x-y signal.

Specifically, this vector is a function of θ, the angle between the eye's optical axis and a line between the eye and the instrument

$$R = K\sin\theta \tag{1}$$

where $K = 3.5$ mm. (typical)

SOURCE CONSIDERATIONS

There are four properties of light that must be considered during oculometer design: power, spectral bandwidth, collimation angle, and beam area. The constraints on each of these properties will now be discussed.

POWER

In order to determine the irradiance required by the oculometer a compromise must be reached between the maintenance of safe illumination levels and providing adequate power for good signal-to-noise ratios. The irradiance at the eye (power per unit area) may be calculated as follows:

$$H = \frac{N_\lambda A_s \Omega}{A_B} \Delta\lambda \, T \tag{2}$$

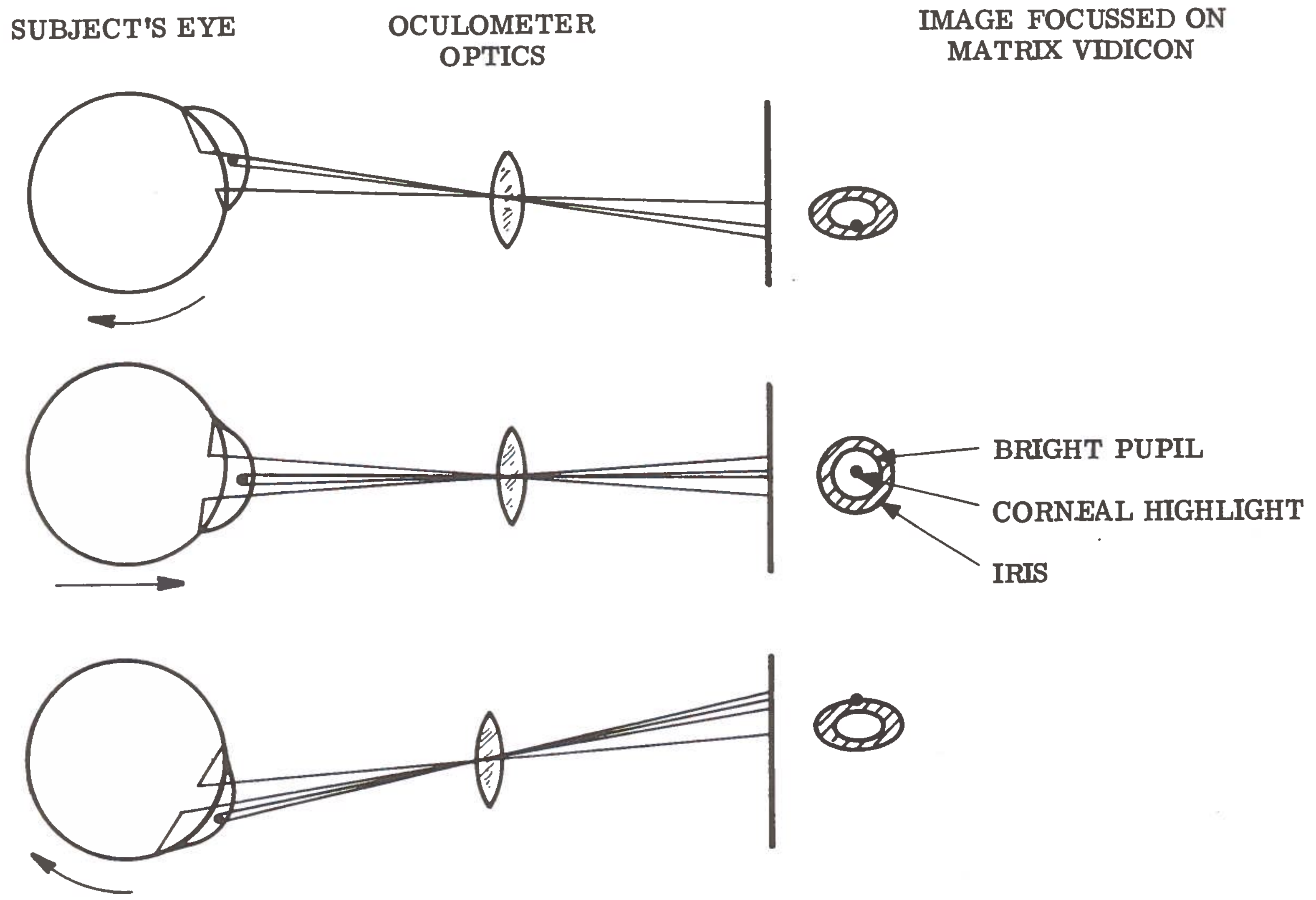
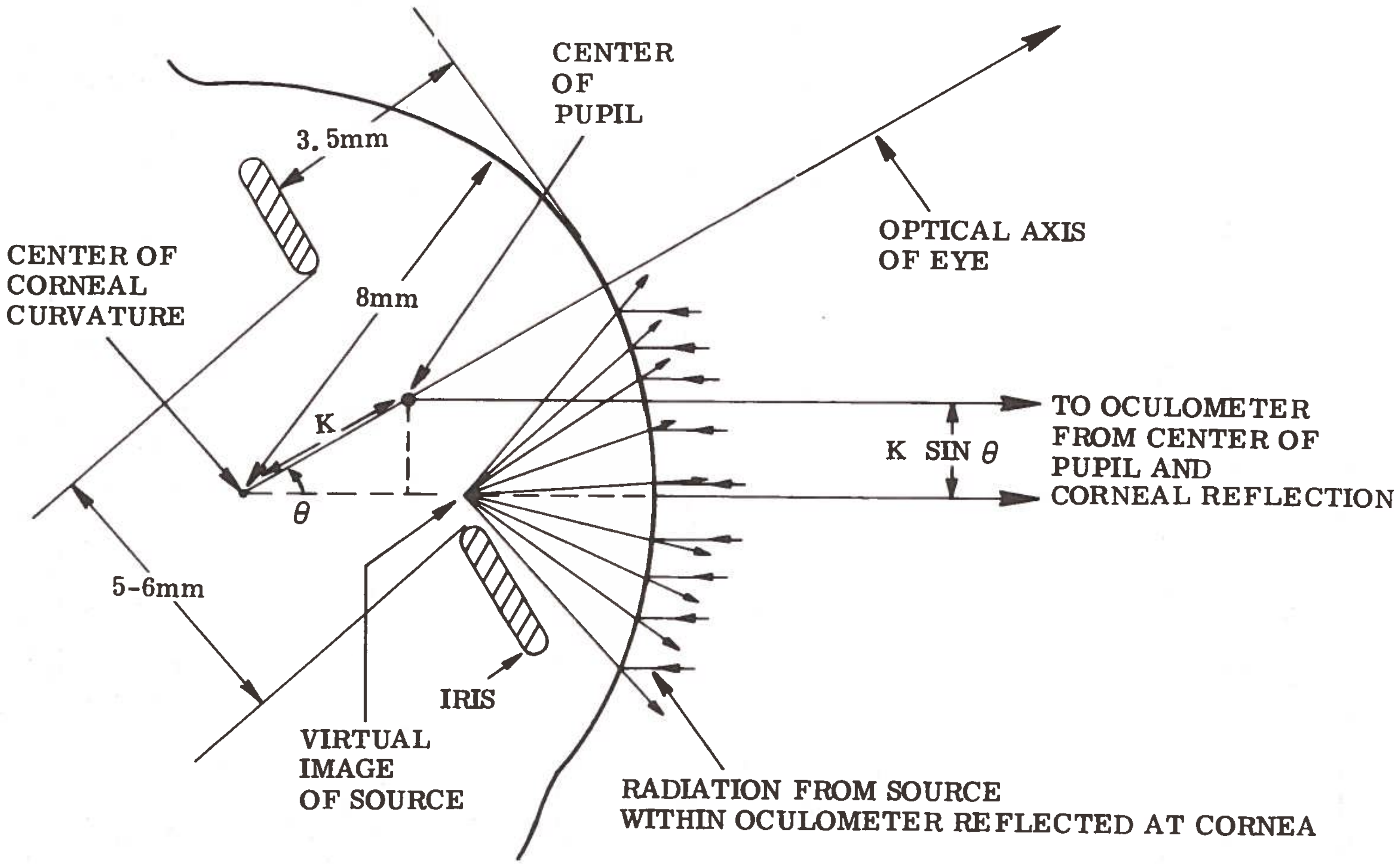


Figure 3. Detection Principle



Displacement of corneal reflection from center of pupil, K Sin θ, is proportional to the angular direction, θ, of the eye, and is independent of the position of the eye.

Figure 4. Eye Parameters

where

H = irradiance at eye (w/cm^2)

N_λ = radiance of source

= 125 $w/cm^2sr.$ for 3200°K black body (e=.7)

A_s = area of source which is projected

= .015 cm^2

Ω = solid angle subtended by the relay lens

= 0.5 sr.

A_B = area of beam at eye space

= 20 cm^2

$\Delta\lambda$ = % spectral energy transmitted by infrared filter

= 10% for Corning CS-7-69

T = transmission of optics including beamsplitter

= 20%

$$H = \frac{(125\ w/cm^2 sr)\ (.015 cm^2)\ (0.5\ sr)\ (.10)\ (.20)}{20 cm^2}$$

$$= 930 \mu w/cm^2$$

This agrees closely with the actual value measured by a radiant flux meter (800µ watts/cm^2) and is considered to be a safe level since the irradiance at the earth's surface from the sun is over 100X higher. For a more detailed discussion of eye safety, see Reference 4.

SPECTRAL BANDWIDTH (FIGURES 5,6)

The spectrum of the beam is limited to the range of .7µ to 1.1µ by a Corning filter CS-7-69. The lower limit of a .7µ is set just outside the response of the eye so that the beam will not be a distraction to the subject. Since the matrix vidicon in the receiver is insensitive to wavelengths above 1.1µ, radiation above 1.1µ serves no useful purpose and only heats the interior of the eye.

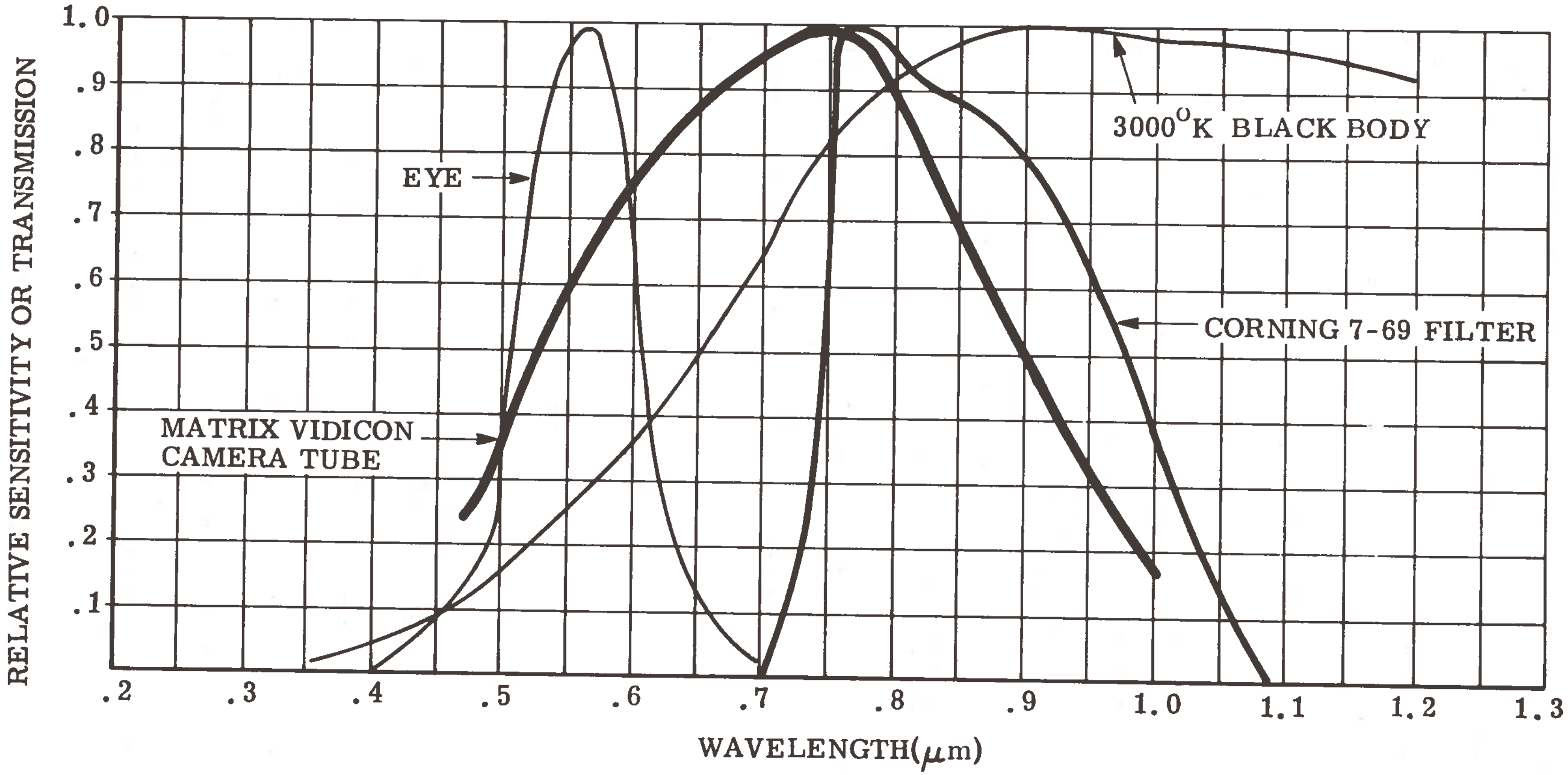


Figure 5. Spectral Sensitivity (System Components)

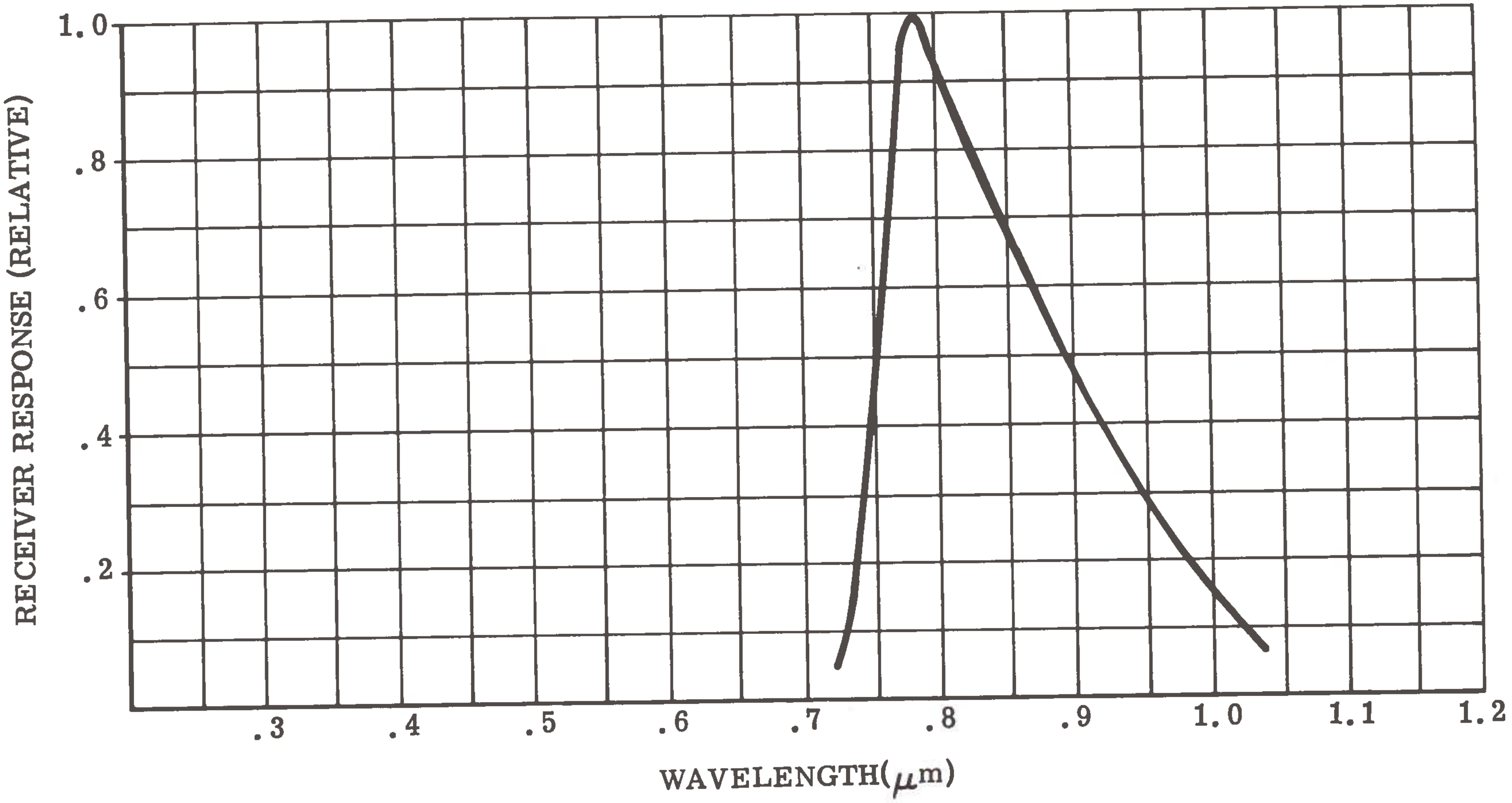


Figure 6. System Spectral Response

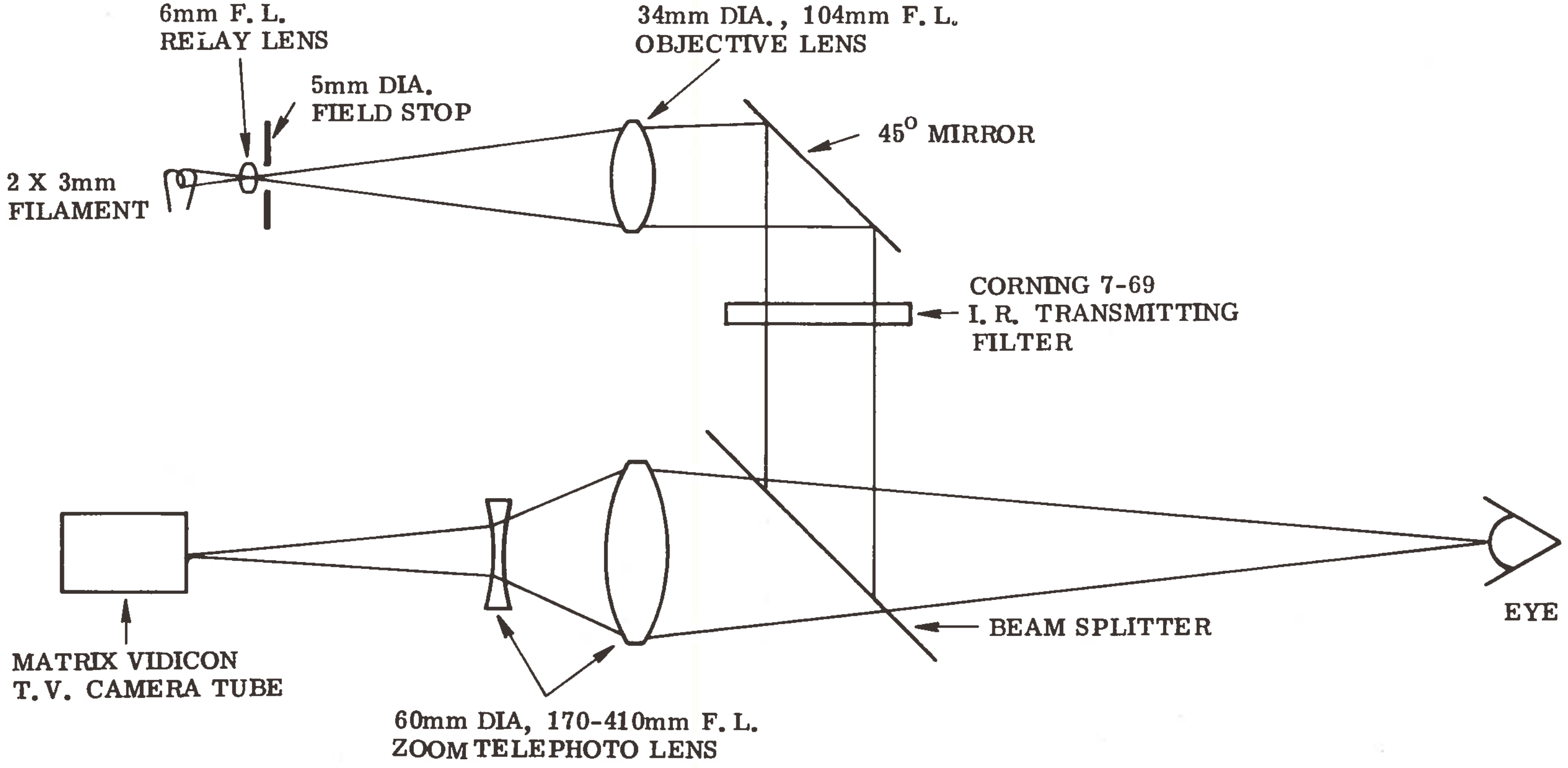


Figure 7. Portable Oculometer Optics

AREA

The diameter of the beam in the plane of the subject's eye should be several pupil diameters so that the tracking mirrors can easily follow the eye as it moves about. Since a typical pupil diameter is 5-8 mm, the design beam diameter was set at 50 mm.

COLLIMATION ANGLE

The bright pupil technique employed here requires a beam with a small collimation angle (large f/number) to produce a pupil which is brighter than the rest of the subject's eye and face. As the collimation angle increases, the contrast ratio between the pupil and iris decreases. In the limit, the pupil looks dark compared to the iris.

The collimation angle of the instrument was designed to be adjustable over a range of f/10 to f/60.

OPTICS (Figure 7)

The projection optics are a straightforward arrangement employed by many slide or movie projectors. To ensure even illumination, a relay lens is used to image the filament of a 100-watt quartz iodine lamp onto the objective lens. This lens in turn images the relay lens at infinity. The beam is directed at the subject's eye by a pair of mirrors mounted on galvanometer shafts.

RECEIVER

The receiver consists of an 85 to 205 mm zoom telephoto lens with a 2X extender and extension tubes to image the eye onto the faceplate of a matrix-vidicon television camera tube. The lens can be adjusted so that the pupil, about 5 mm in diameter, extends to approximately 100 TV lines. Earlier it was stated that

$$\theta = \sin^{-1} \frac{R}{3.5 \text{ mm}} \qquad (3)$$

where θ = the angle between the eye's and the oculometer's optical axis

R = the distance between the center of pupil and the corneal highlight

Since there are 20 TV lines/mm at the eye, this becomes

$$\theta = \sin^{-1} \frac{R}{70 \text{ lines}} \tag{4}$$

Since R can be determined to one TV line, then $\Delta\ \theta$, or the resolution of the oculometer is ≃ 1° for small angles.

When using signal averaging, R can be determined to better than one TC line and the resolution becomes approximately 0.2° for 0.1 second time constant.

ELECTRONIC CONTROLLER DESIGN

OPERATION OF THE IMAGE PROCESSING ELECTRONICS

The digital-analog computing system calculates from the standard TV-video signal the relative positions of the center of the pupil image and the center of the corneal highlight image, and outputs this information as an x, y analog signal. Two mirror control signals that drive the galvonometer mirrors are also computed.

The computing electronics are synchronized to the TV raster scan. The output signals are updated with each video field (i.e., every 16.6 milliseconds). Unlike previous oculometers, this system does not track the pupil and corneal image. Each positional calculation is performed totally independent of the previous one. For this reason, except in the case of extreme head movements, the loss-of-track situation cannot occur. Therefore, recovery of positional data from things such as blinks and fast eye movements does not require time-consuming search techniques.

The center of the pupil and the center of the corneal highlight are calculated in real time by a center-of-mass technique. The TV image is mapped onto an (x,y) coordinate system (Figure 8). When the raster scan crosses an edge of the pupil or corneal highlight image, a pulse is generated which causes the (x,y) coordinates of the beam to be added to an accumulated sum which is stored in a register. There are four such registers: pupil x, pupil y, corneal x, corneal y. At the same time, a counter containing the number of edge encounters is incremented by one. At the end of the field, the contents of these six registers are loaded into their respective storage buffers, whereupon they are converted into analog signals by digital-to-analog converters. The (x,y) coordinates of the center of the pupil and the center of the corneal highlight are computed in parallel by four analog dividers, as follows:

$$PX = \text{pupil edge x coords./number of pupil edge encounters} \tag{5}$$

$$PY = \text{pupil edge y coords./number of pupil edge encounters} \tag{6}$$

$$CX = \text{corneal edge x coords./number of corneal edge encounters} \tag{7}$$

$$CY = \text{corneal edge y coords./number of corneal edge encounters} \tag{8}$$

Since the pupil covers about 100 TV lines, there are about 200 data points contributing to the calculation. The corneal highlight produces about 10 data points per calculation. The final vector is computed by two differential amplifiers:

$$VX = CX-PX \tag{9}$$

$$VY = CY-PY \tag{10}$$

DESIGN DETAILS (Figures 8-13)

The xy position of the raster scanning beam is determined as follows. An 8MHz digital clock is synchronized to the horizontal sync pulses of the video signal. Synchronization is necessary to eliminate phase error of the clock which will otherwise occur for each horizontal scan. The clock drives a digital counter which is reset to zero with each horizontal sync pulse. The contents of this counter thus represents the x-coordinate of the scanning beam. The y-coordinate is generated in another counter that is reset to zero with each vertical sync pulse, and is incremented by one with each horizontal sync pulse. The interlacing of horizontal scans will produce a small error in the contents of the vertical position counter. This can be compensated for by complementing an additional bit at the end of each field. This bit then becomes the least significant bit of the vertical position register.

Because about one microsecond is required for the adders to stabilize, the inputs to the horizontal pupil and corneal adders must be buffered. In the case of the corneal adder, the input must be double-buffered, since the passage of the beam over the corneal highlight image can occur in less than half a microsecond. Care must be taken in the timing of the control pulses, otherwise, bits will be lost. Details of the system timing are shown in Figure 13.

The dynamic range of the analog dividers is limited. Therefore, the outputs of the six digital-to-analog converters must be scaled so that the voltages fall within the acceptable range of the dividers. The outputs of the dividers must then be rescaled to compensate for the earlier scaling.

The mirrors are driven by two gated integrators, whose inputs are the voltage differences between the true (x,y) pupil position and the desired (x,y) pupil position. The integrator input is set to zero when the pupil image is in the center of the TV screen. Any positional offset causes the integrators to integrate the error, thereby rotating the mirrors until the pupil is again in the center of the TV screen. This system tends to oscillate unless the mirror rotation is constrained to the period of time when the scan is not crossing the pupil edge.

A useful signal also available from the electronics is the pupil edge counter. The value of this counter represents twice the number of TV lines covered by the pupil image. In other words, the value in the pupil edge counter is proportional to the diameter of the pupil. By calibrating this signal with known-diameter, simulated pupils, an accurate real time pupil diameter measurement can be performed without constraining head movement.

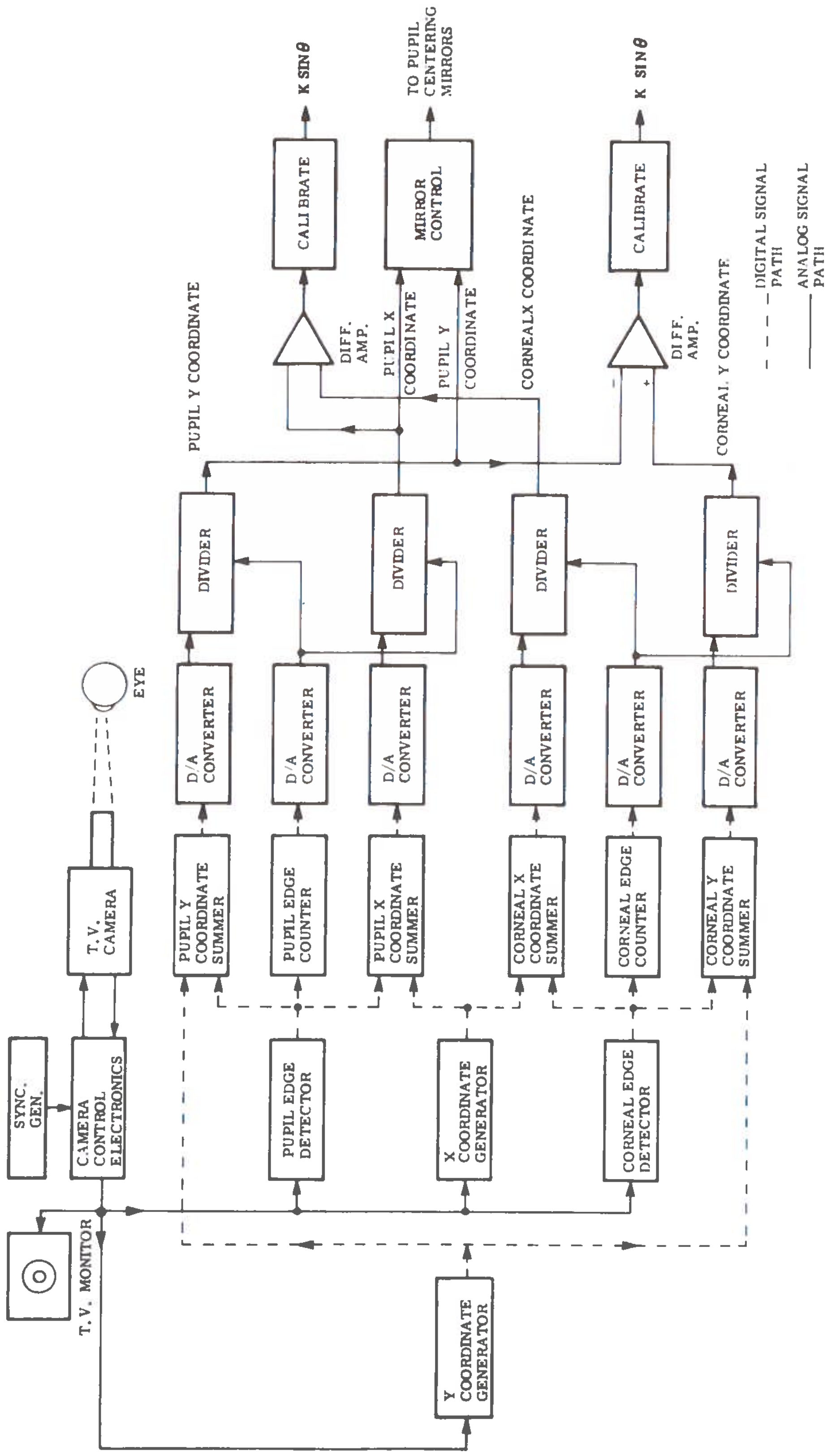


Figure 8. System Diagram

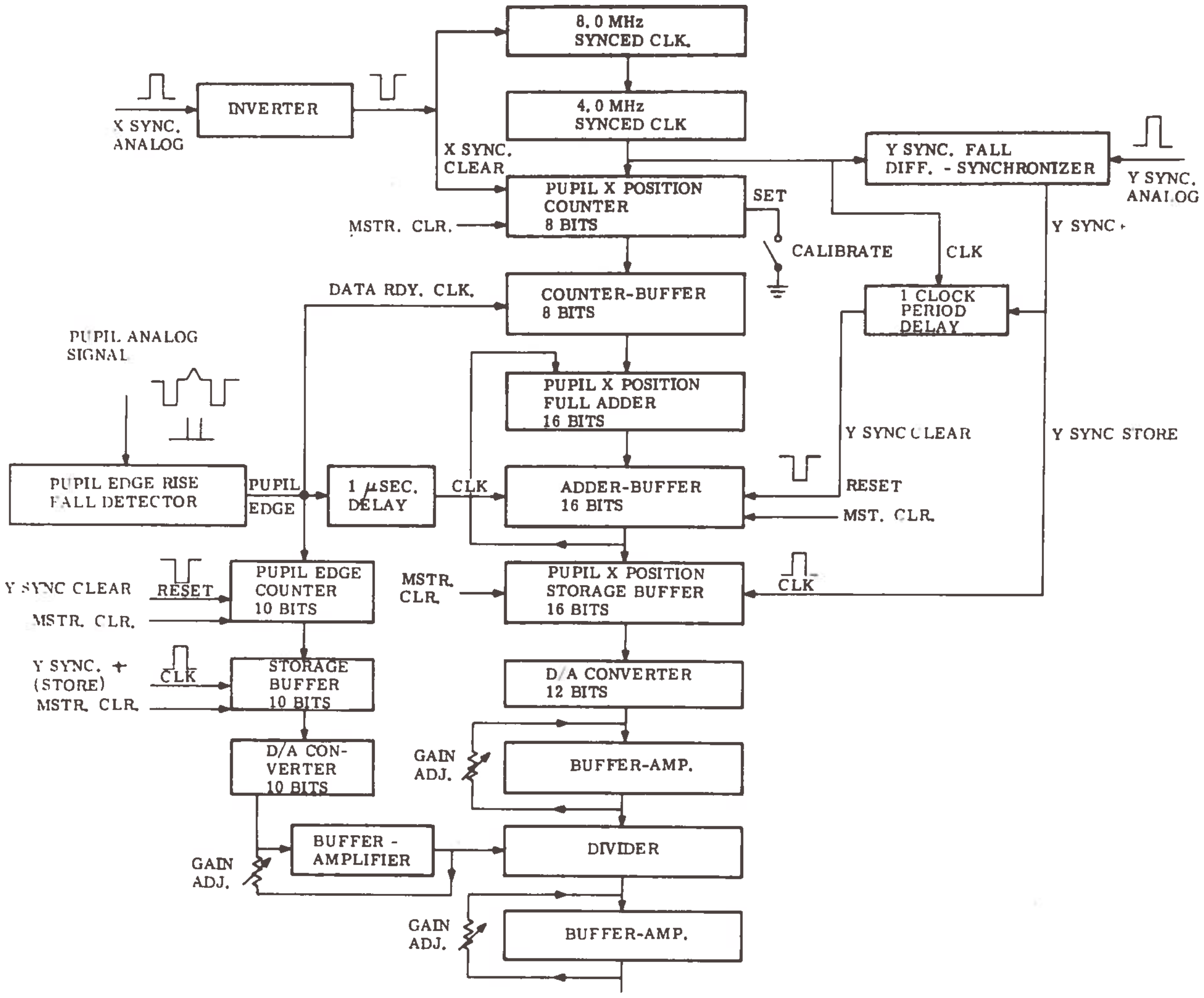


Figure 9. Pupil X Position Circuit

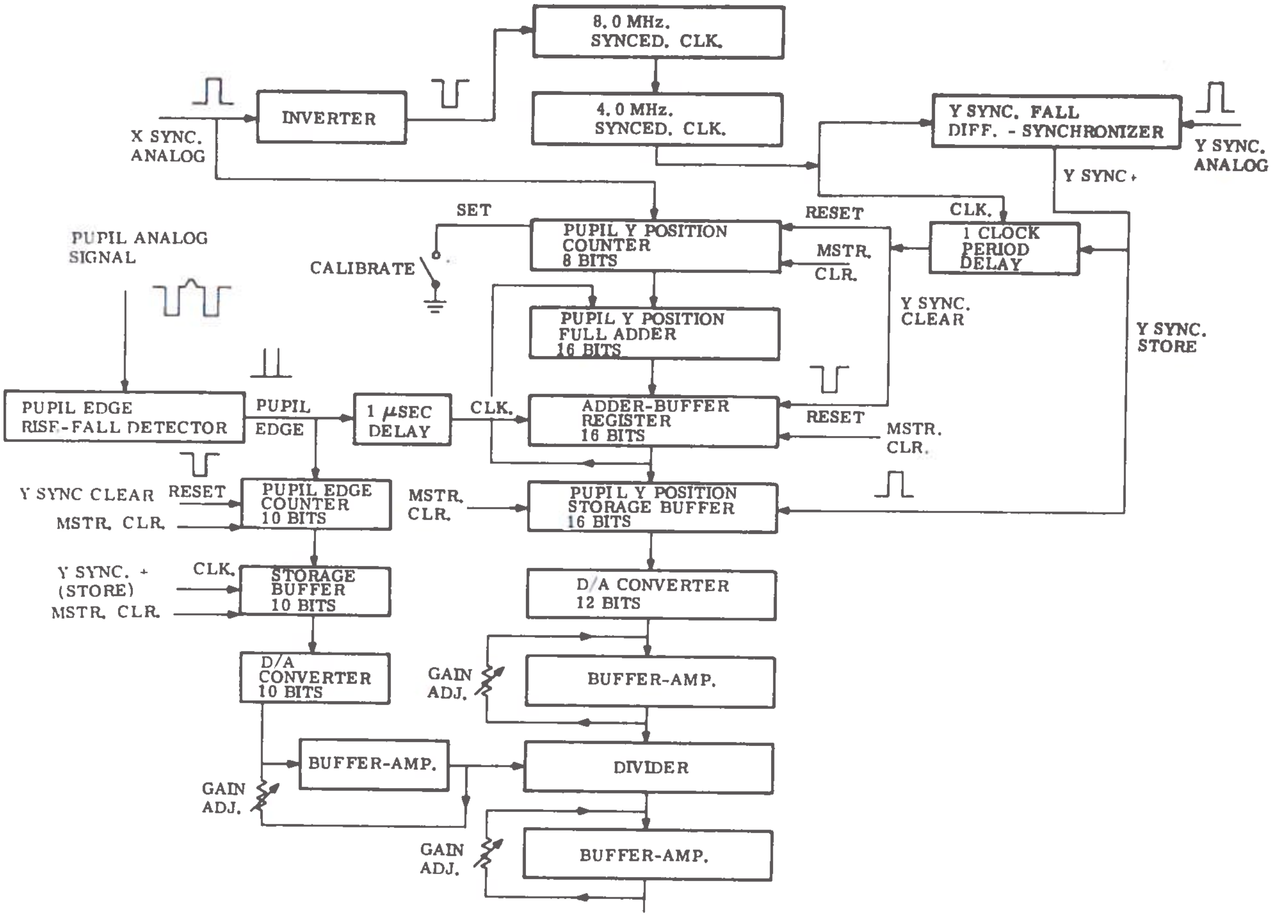


Figure 10. Pupil Y Position Circuit

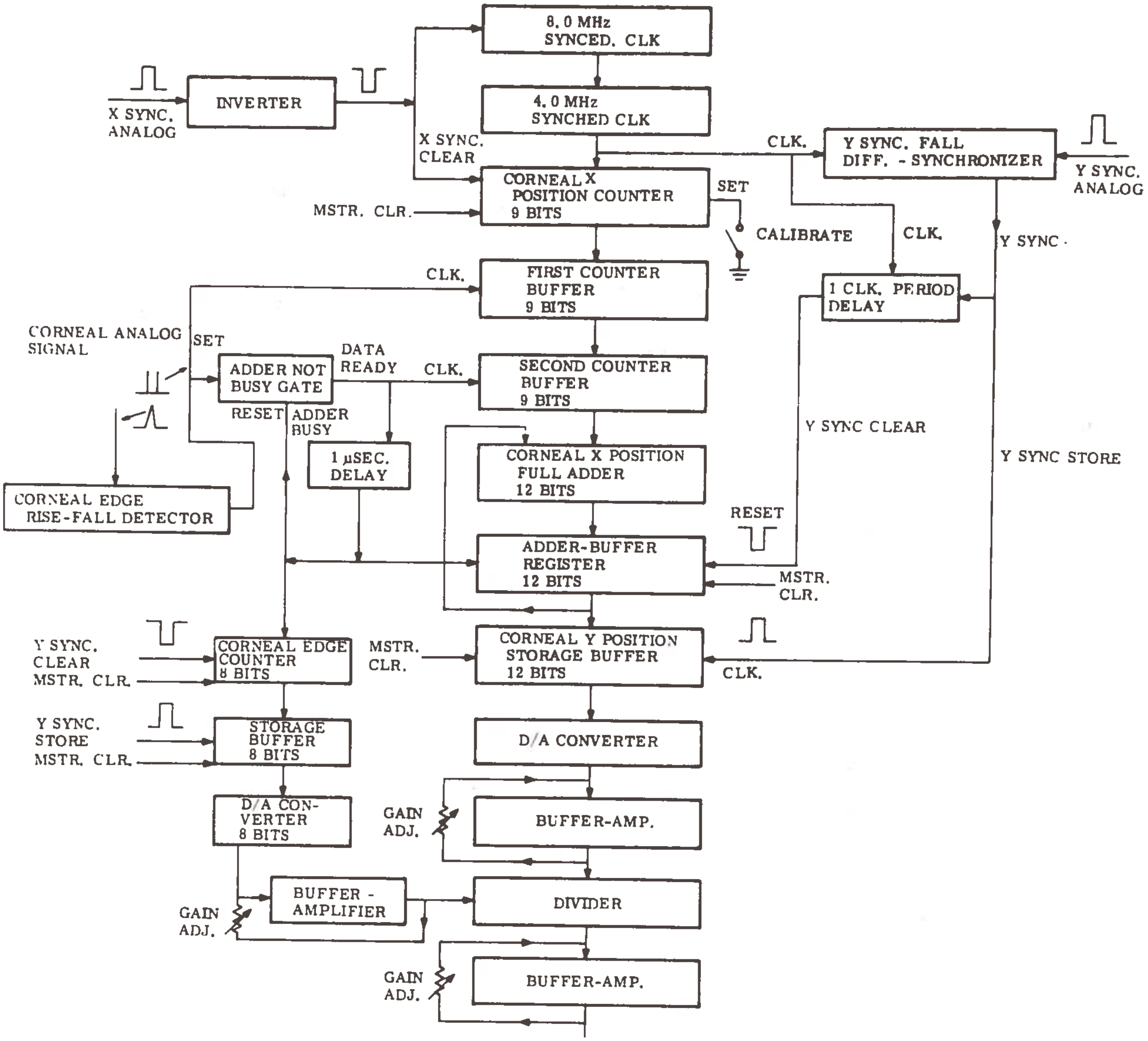


Figure 11. Corneal X Position Circuit

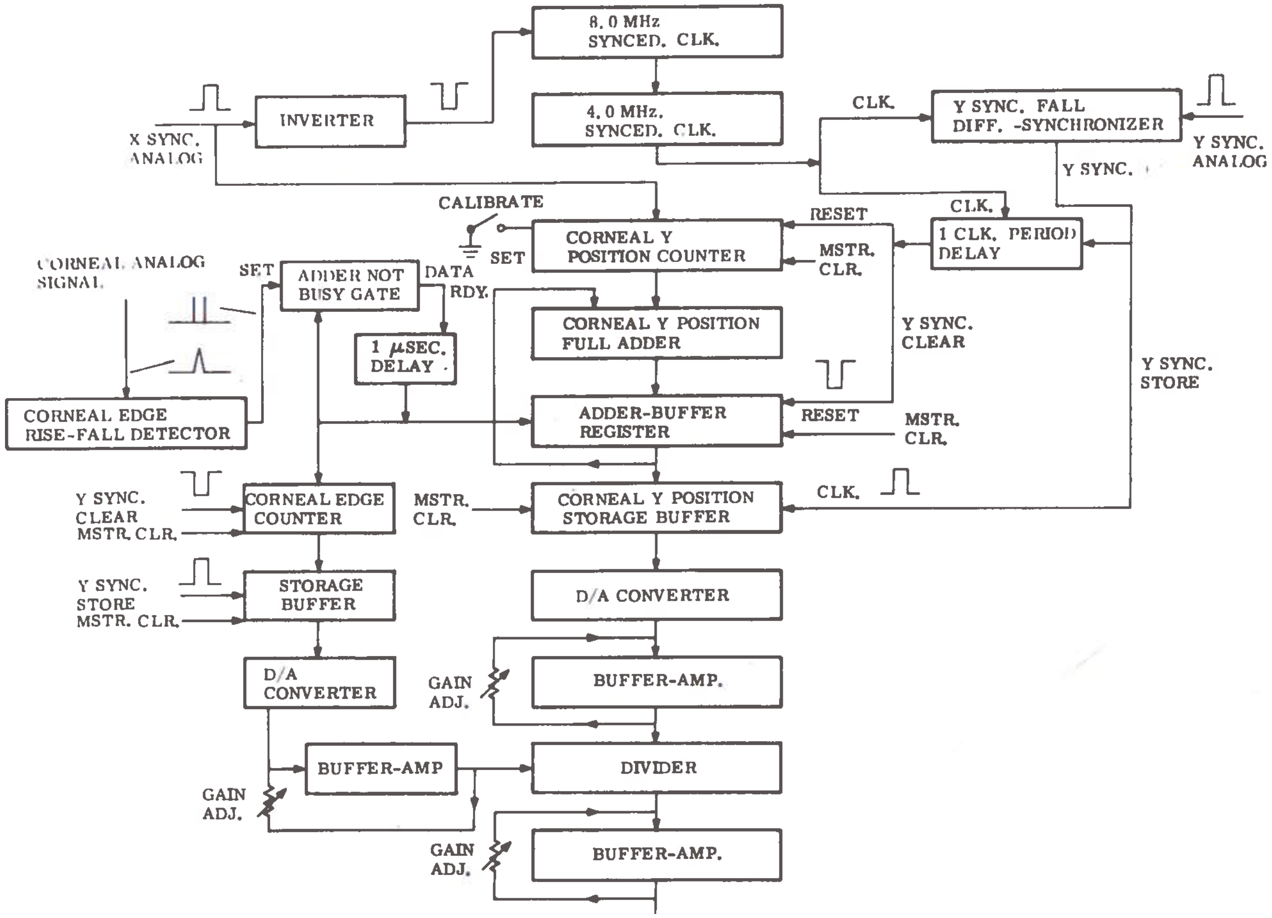


Figure 12. Corneal Y Position Circuit

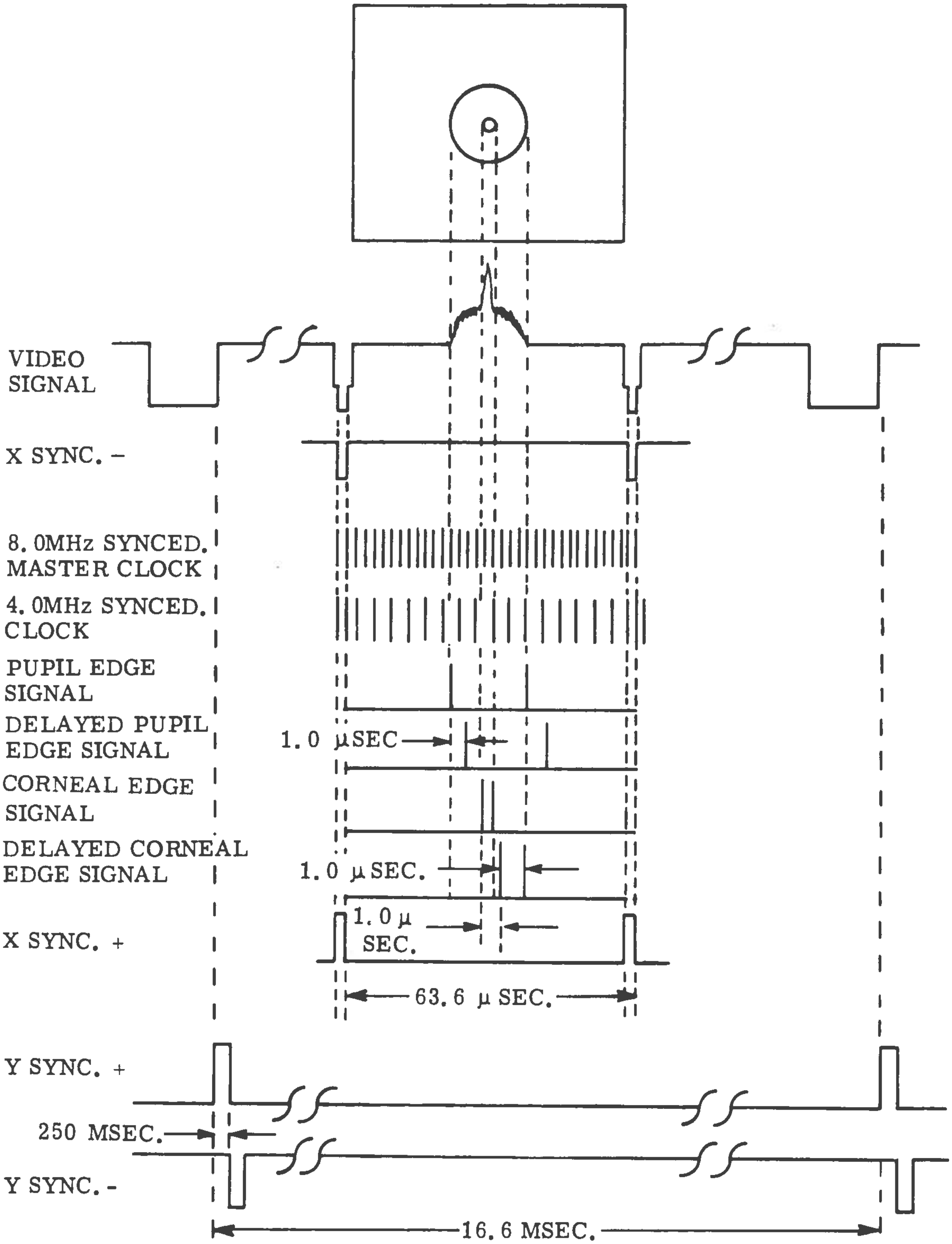


Figure 13. Timing and Control Signals

EVALUATION OF SYSTEM PERFORMANCE

The work reported here has consisted primarily of the design and development of the portable oculometer system. During the final stages of this work, preliminary measurements have been made to establish general performance characteristics.

GENERAL

At present, the portable oculometer has been operated only in a laboratory environment for the purpose of circuit testing, debugging, and preliminary evaluation. System performance during this phase has been very encouraging. Tests were made during which an operator tracked images displayed on rear projection screens and on video monitors in both partial darkness and with full room lights. The results indicate that the system will be usable immediately in both simulator and laboratory environments. In-vehicle tests will be conducted during the coming year in conjunction with two active TSC projects for the purpose of establishing practical operating characteristics and constraints when used on-road. The results of these and other experimental applications of the system will be reported as they become available.

ARTIFICIAL EYE

To aid both system testing and measurement of performance characteristics, an artificial eye was used. The eye, designed and constructed by Hillsman (Ref. 3), was machined and polished out of methylmethacrylate plastic (n=1.49), as shown in Figure 14. The dimensions used match very closely those of an average human eye, thus allowing extended system testing without the use of human subjects. The eye was mounted in a gimboled mount (Figure 15) which allowed calibrated angular measurements to be taken (Figures 16-18).

PERFORMANCE MEASUREMENTS

The values of the measured parameters were established using either the artificial eye or a variable diameter pupil calibrator.

A) Angular field-of-view (human eye):
    Horizontal: $\pm 20^{\circ}$
    Vertical: $\pm 20^{\circ}$

B) Angular sensitivity:
   Horizontal: 86 mv/deg (Figure 17)
   Vertical: 97 mv/deg (Figure 18)

C) Angular Resolution: <1°

D) Angular Linearity: ±0.15°

E) Random Noise Level Around Fixation Point: < 7 mv (0.08°) with 50 Hz bandwidth

F) Pupil Diameter (Figure 19)
   Range: 1-10 mm
   Sensitivity: 1.16 v/mm

G) Head Motion Range:
   Horizontal: 50 cm
   Vertical: 50 cm
   Along Optical Axis: 5 cm

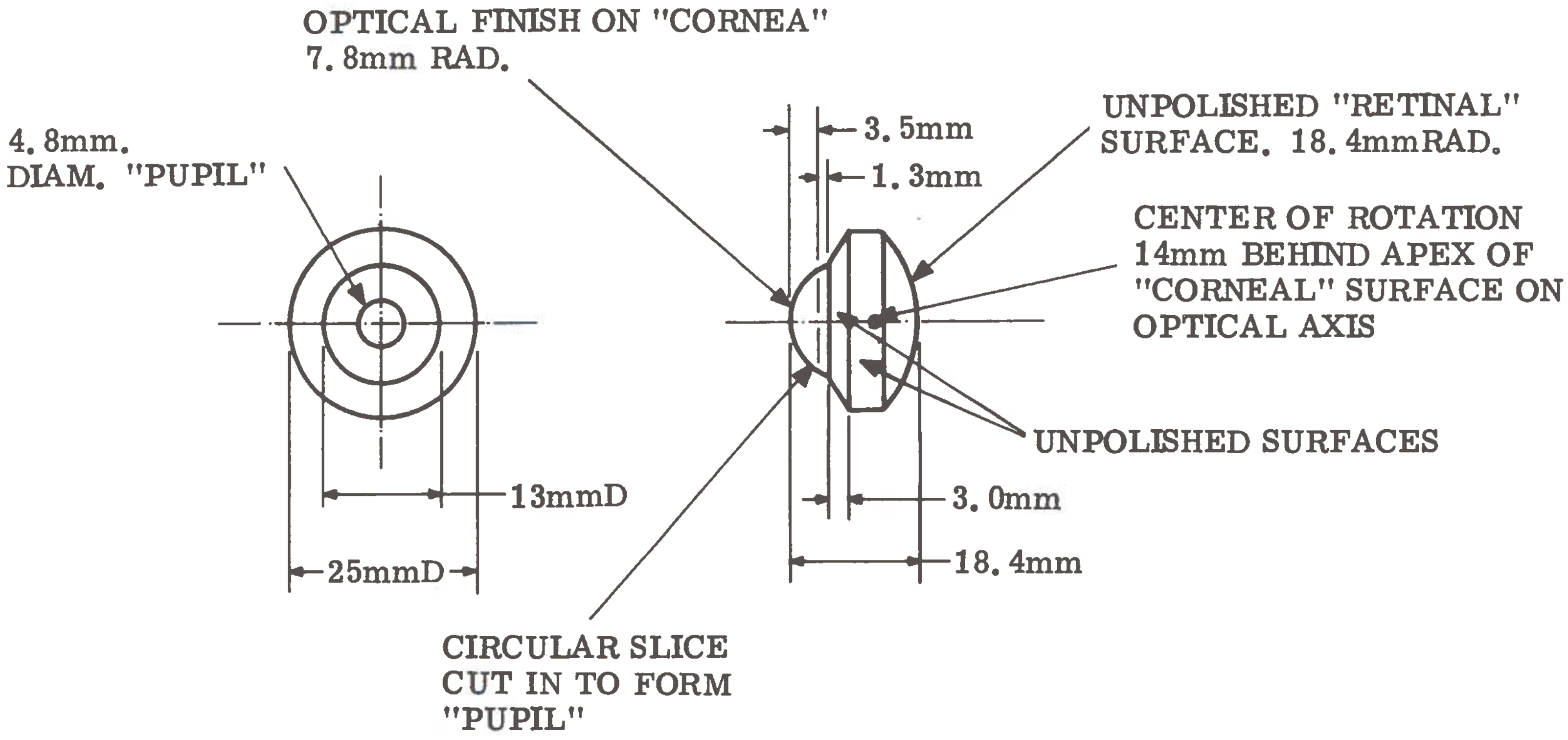


Figure 14. Aritifical Eye

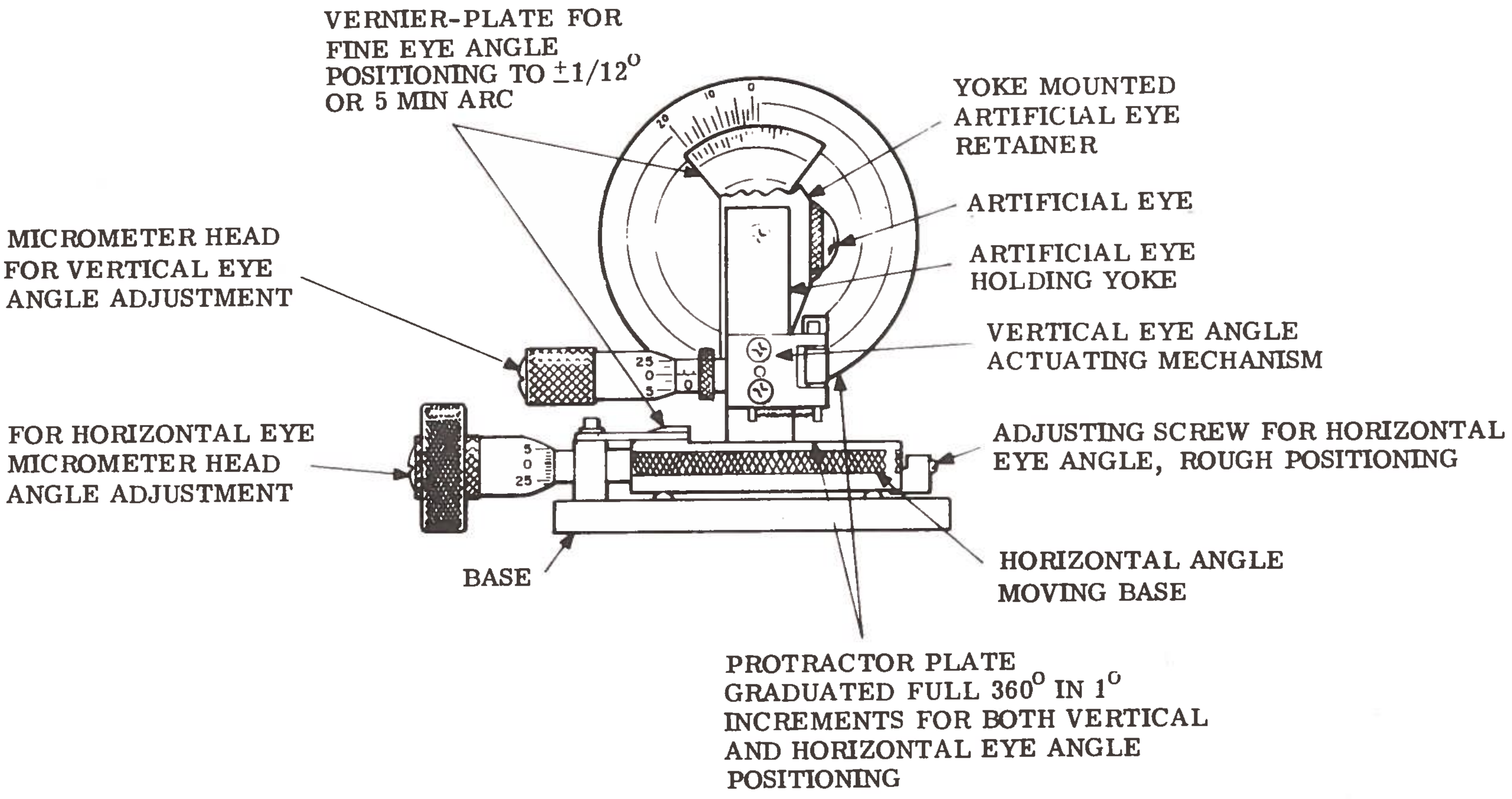


Figure 15. Calibration Test Fixture

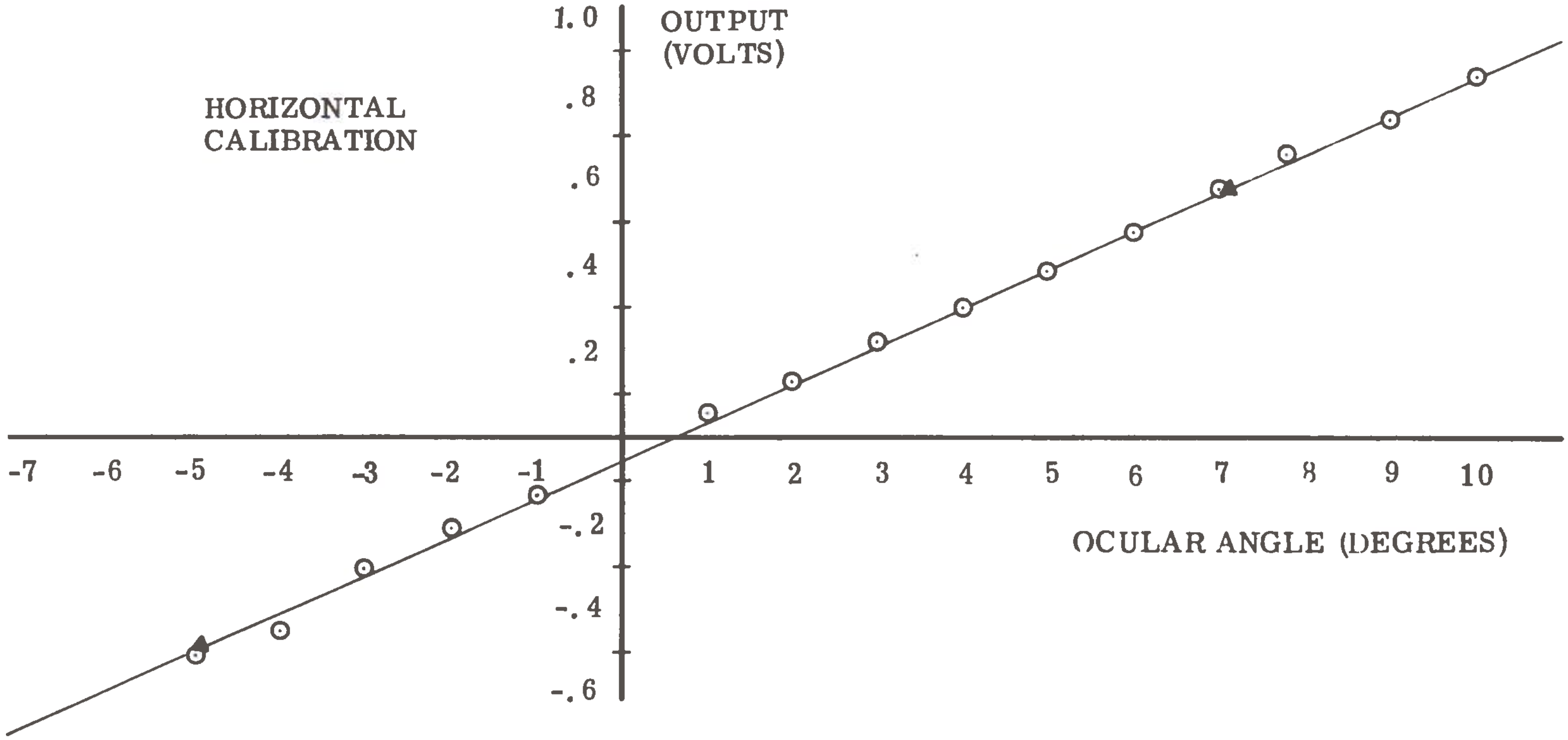


Figure 16. Horizontal Field-of-View

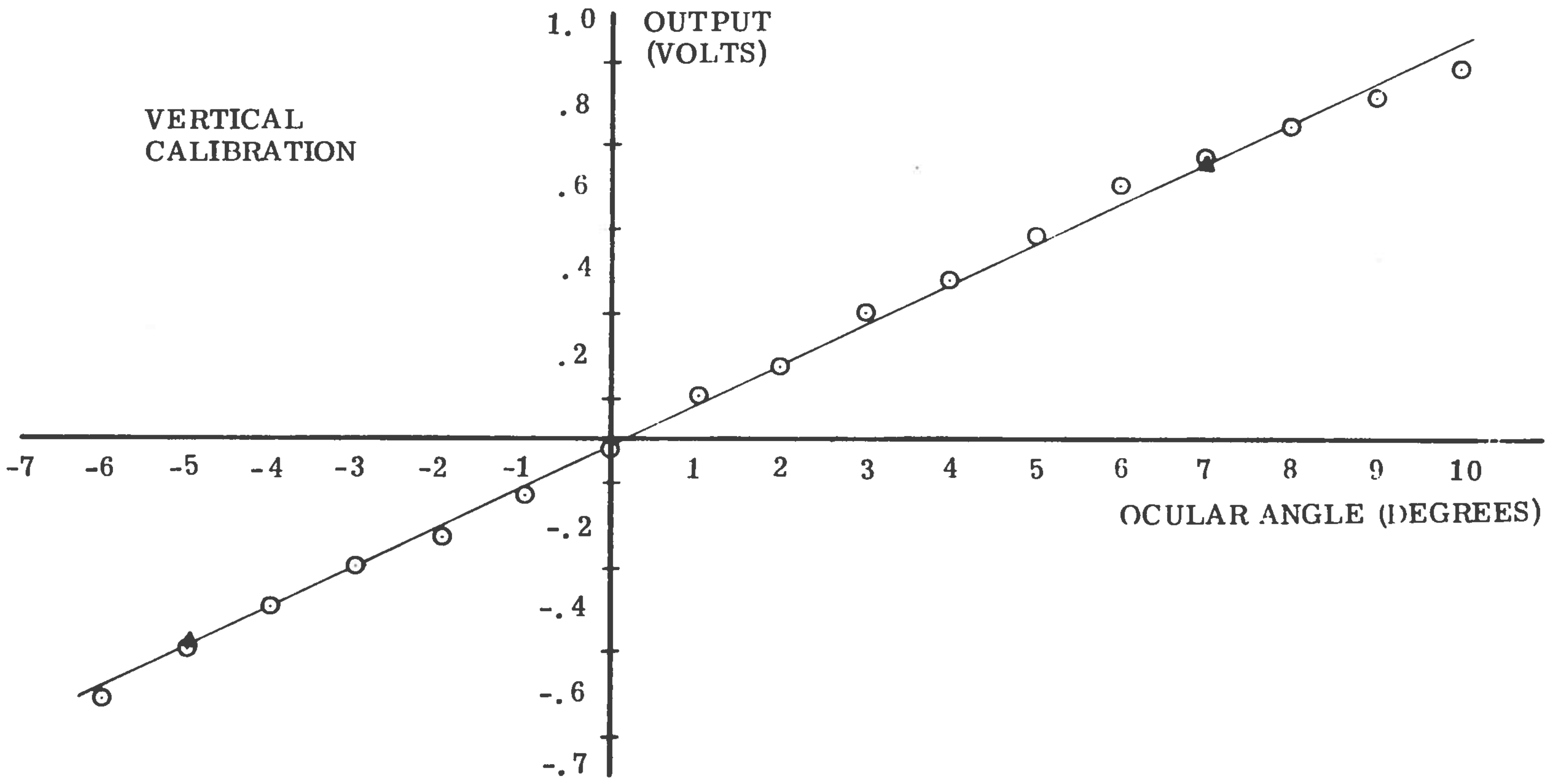


Figure 17. Vertical Field-of-View

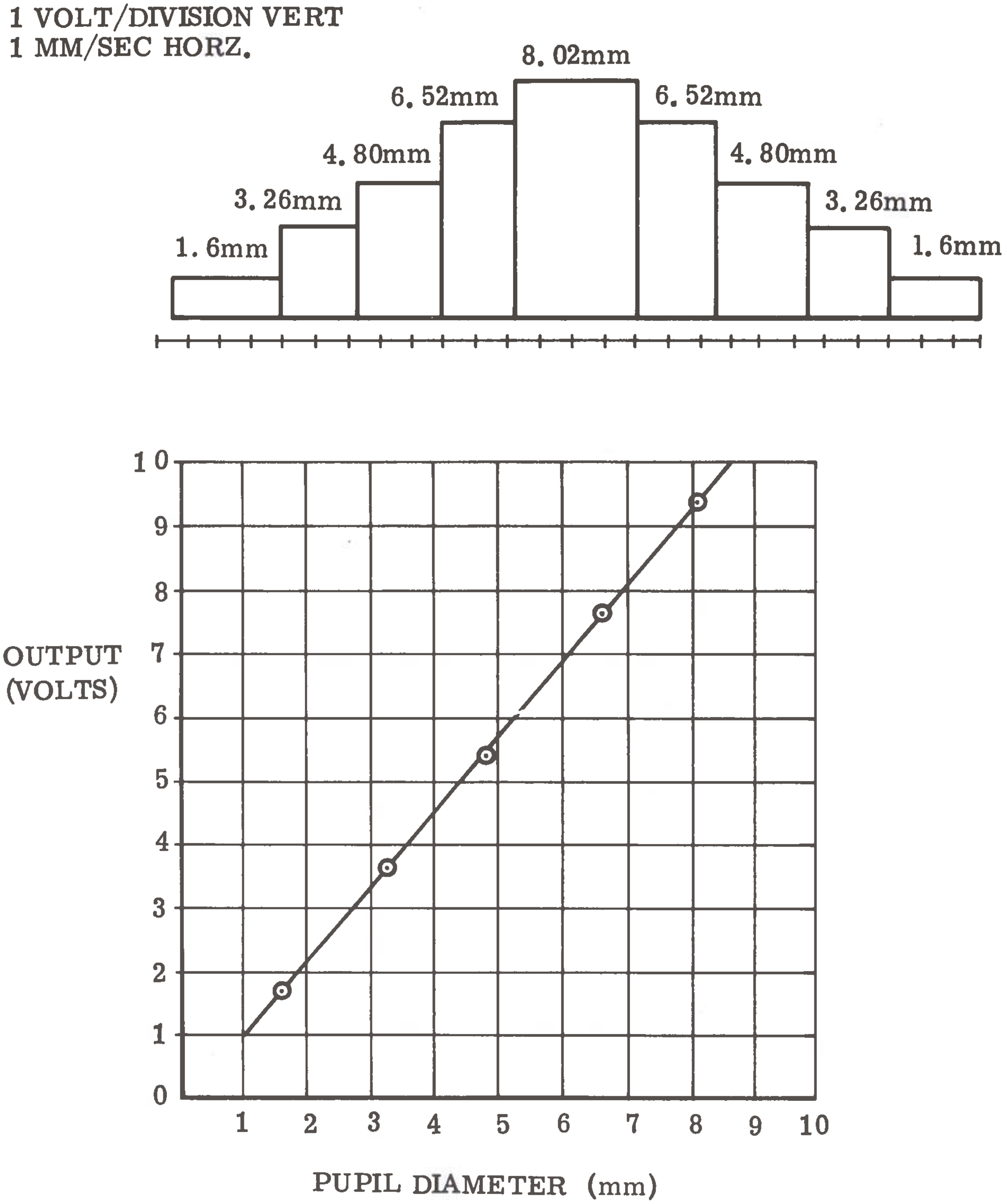


Figure 18. Pupil Diameter Calibration

APPLICATIONS

In general, applications of visual performance measurements can be classified according to the following list of instrument operating modes:

1. Dynamic measurement of visual fixation point referenced to a pre-calibrated two-dimensional surface,
2. Dynamic measurement of visual fixation point referenced to a changing scene,
3. Dynamic measurement of involuntary eye motions -- saccades, drift, pupil response, etc.,
4. Correlation of voluntary and involuntary eye motions to other physiological and psychological variables,
5. Real-time interactive use of eye motions as a control device.

Examples of some of the experimental studies pertinent to transportation problems have been listed and correlated to the above categories in Table 1. Table 2 correlates these operating modes with available eye motion instrumentation so that relative advantages and disadvantages of the various techniques can be examined.

INITIAL EXPERIMENTAL VALIDATION

Three experiments have been selected to validate and demonstrate the use of the portable oculometer in several of the possible operating modes. The first is a test of pupil response variation as a function of fatigue. This involves measurement of an involuntary visual parameter without scene reference. Next is an experiment involving measurement of pupil response referenced to the observer's attention point in a scene. Finally, the instrument will be used to observe variations in visual tracking behavior occurring from intoxication and fatigue. These initial experiments have a dual purpose. The results are of immediate interest to several of our related programs, and the experiments can be used to establish practical operating characteristics and limitations.

TABLE 1. TYPICAL EXPERIMENTS

	Instrument Operating Mode		
	Voluntary Eye-Motions		Involuntary Visual Measurements
Applications	Fixed Scene	Video Reference	
Operator Measures			
(1) Fatigue Effects			X
(2) Effects of Alcohol and Drugs			X
(3) Visual Perception	X	X	
(4) Attention	X	X	
(5) Skill Determination	X	X	
Operator-Vehicle Interaction			
(1) Dashboard/Cockpit Design	X		
(2) Effects of Visual Distractions		X	
(3) Front and Rear Visibility		X	
Operator-Environment Interaction			
(1) Road and Sign Design		X	
(2) Reduced Visibility Effects Nighttime/Fog		X	
(3) Vehicle Lighting Studies		X	

TABLE 2. COMPARISON OF INSTRUMENT OPERATING MODES

Eye Measurement Techniques Instrument Operating Modes	Remote Photography	Head-MTD Photography	Head-MTD Photosensors	Electro-Oculography	Contact Lens	Portable Oculometer
Location of Fixation Point on Two-Dimensional Surface	X	X	X	X	X	X
Location of Fixation Point Referenced to Changing Scene		X				X
Measurement of Involuntary Eye Motions and Pupil Response	X	X	Partial	X	X	X
Correlation of Other Physiological Measurements to Eye Motions			X	X	X	X
Use of Eye Motions in Control Loop						X

APPENDIX A

OCULOMETER VALIDATION EXPERIMENTS

PUPIL DIAMETER VARIATION AS AN INDICANT OF FATIGUE

Research by Lowenstein, Feinberg, & Lowenfeld (Ref. 5) has demonstrated oscillations in the pupil diameter of fatigued subjects who had no known neurological pathology. The oscillations or contractile waves were measured under complete darkness with the subject fixating on a dim light. For the purpose of the measurements, the subjects were dark-adapted and tested over a ten minute period. Measurement of this phenomena might be of use in determining whether individuals such as pilots, air controllers, and railway enginemen are in a fatigued state. The value of this measure would be enhanced if the measures could be made under normal illumination and without a long adaptation period.

In order to determine the feasibility of using the technique under normal lighting conditions, an experiment will be performed using the TSC oculometer. The oculometer will be used to measure the pupil diameter of subjects under fatigued and non-fatigued conditions.

TSC personnel between the ages of 21 and 45 years with no known neurological pathology will serve as subjects.

Procedure: Subject's pupil diameter and pupil diameter variability will be measured under four conditions.

1. normal lighting after a normal night's sleep
2. darkness after a normal night's sleep
3. normal lighting after remaining awake for 24 hours
4. darkness after remaining awake for 24 hours.

Measurements under normal lighting will be made with the subject looking at a featureless back projection screen with an average illumination of approximately 50 foot-candles.

Measurements in darkness will be made with the subject fixating on a dim red light (one foot-candle). The measures will be made after ten minutes of dark adaptation.

VARIATION OF PUPIL SIZE AS AN INDICANT OF ATTENTION

It has been suggested that if one does not wish to see a repugnant scene, he at times can shut it out of his mind. Hess (Ref. 6) in a study of the variations of the pupil area as a function of the interest or attention value of stimuli, has concluded that positive interest produces a larger pupil and negative interest, a smaller pupil.

Due to deficiencies in the measurement techniques, such as lack of brightness, contrast, and color-control of the stimulae and inaccurate methods for measuring pupil area, his results have been questioned. However, if such a correlation between pupil size and attentional state exists, it might prove quite useful as a research tool.

Since the TSC oculometer is capable of simultaneously measuring both fixation point and pupil area, it becomes the ideal instrument to test this hypothesis.

Procedure; For this experiment, a film is used which contains scenes that a viewer will actively desire not to watch. Measurements of fixation point and of pupil diameter will be recorded during these scenes and compared with a reference set of non-repugnant scenes. Independent measures will be made to establish scene brightness and contract. If the Hess hypothesis is correct, pupil diameter will increase as a function of attentional state.

APPENDIX B

OTHER EYE MOTION MEASUREMENT TECHNIQUES

1. Photography (or video recording). The face of the observer is recorded on film or tape. At a later time, the direction of gaze may be deduced by comparison to calibration views. A split-image (or insert) or a second camera can be used to record the scene that is available for viewing.

2. Head-mounted camera (cine or video). The visual scene available to the observer and a spot of light reflected from his eye are superimposed in a final image. The position of the eye spot on the film is proportional to the eye position.

3. Photo-electric sensors. Head-mounted photosensors are positioned to view the sclera-iris junction (sclera = white of the eye). As the eye moves, the proportion of sclera in the field-of-view changes and correspondingly, the brightness of the field changes.

4. Electro-oculography (EOG). The retinal-corneal potential difference creates an electrostatic dipole, the rotation of which can be sensed by surface electrodes placed around the eye.

5. Contact lens. A contact lens (the larger scleral type) moves with the eyeball. A mirror attached to the contact lens may, therefore, be used to reflect a beam of light in much the same manner as the head-mounted camera.

The most precise measurements (down to a few minutes of arc) are obtained with the contact lens; but this is also the most uncomfortable technique. The most comfortable techniques are photography, head-movement measurements, and the oculometer, since all of these are remote systems. Head-mounting is required for photo-electric sensors, head-mounted camera, EOG, and contact lens techniques. Table 3 compares the techniques in terms of operational parameters and constraints.

TABLE 3

MEASUREMENT TECHNIQUE COMPARISON CHART

(Refs. 7 and 8)

EYE MEASUREMENT TECHNIQUE PARAMETER	REMOTE PHOTOGRAPHY	HEAD-MTD PHOTOGRAPHY	HEAD-MTD PHOTOSENSORS	ELECTRO-OCULOGRAPHY	CONTACT LENS	PORTABLE OCULOMETER
ANGULAR FIELD-OF-VIEW (DEGREES)			±20° HORIZ +10) VERT -20)	±50°	±10°	±20°
ANGULAR SENSITIVITY (DEGREES)	DEPENDENT UPON FILM RESOLUTION AND OPTICAL MAGNIFICATION		.25° HORIZ 1° VERT	1°	±0.001°	1°
SYSTEM NOISE LEVEL (DEGREES)	DEPENDENT UPON FILM RESOLUTION AND OPTICAL MAGNIFICATION				0.02°	0.08°
TYPE OF RESTRAINT REQ'D (HEAD, EYE, ETC.)	HEAD CLAMP	HEAD CLAMP AND BITE BAR	SENSORS MTD. ON EYEGLASS FRAMES	HEAD MTD. ELECTRODES	LENS MTD. ON EYE	NONE
LINEARITY (DEGREES)				±1°		±0.16°
OVERALL ACCURACY	>1°	~1°	2°	±2°	±0.01°	±1°
PUPIL MEASUREMENT RANGE (MM.)	1-10 mm	1-10 mm	NONE	NONE	NONE	1-10 mm
DATA REDUCTION REQUIREMENTS	MANUAL ANALYSIS OF PHOTO DATA	MAN. ANALYSIS OF PHOTO DATA	CHART RECORDER OR ANALOG TAPE	CHART RECORDER OR ANALOG TAPE	MANUAL ANALYSIS OF PHOTO DATA	OPTIONS: CHART RECORDER; ANALOG TAPE ON-LINE DIGITAL; VIDEO
DRIFT	NONE	NONE	0.2°/hr.		NONE	NONE
REAL TIME MEASUREMENT	NO	YES (Digitized) NO (Recorded)	YES	YES	YES	YES
COMFORT	HIGH	LOW	MODERATE	MODERATE	LOW	HIGH
COST	LOW	MODERATE HIGH	MODERATE	MODERATE	MODERATE HIGH	MODERATE HIGH

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