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SYSTEM DESIGN STUDY FOR AN OPTIMAL REMOTE OCULOMETER FOR USE IN OPERATIONAL AIRCRAFT

by John Merchant, Ronald Wilson, and Kenneth A. Mason

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

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FOREWORD

Under contracts NASw- 1159 and NAS12-531, Honeywell Radiation Center has developed a new electro-optical method of measuring eye direction. The principal feature of this new method is that it does not require that the device (Oculometer) be clamped, or otherwise fixed, to the subject. A laboratory Oculometer has been constructed. The unique ability of the Oculometer to accurately measure eye direction without interference to the subject has suggested its application for pilot eye fixation monitoring. In this document, the results are presented of a design study, performed by Honeywell Radiation Center, of a remote configuration Oculometer suitable for measuring the eye direction of a pilot, without causing any interference to his normal activities.

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SYSTEM DESIGN STUDY FOR AN OPTIMAL REMOTE OCULOMETER FOR USE IN OPERATIONAL AIRCRAFT

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INTRODUCTION

A number of techniques have been used to measure eye direction, or sense eye motion. Optical techniques involve either film recording or electro-optical sensing of certain eye detail, e.g.,

- sclera/iris boundary
- corneal reflection
- purkinje images
- retinal detail

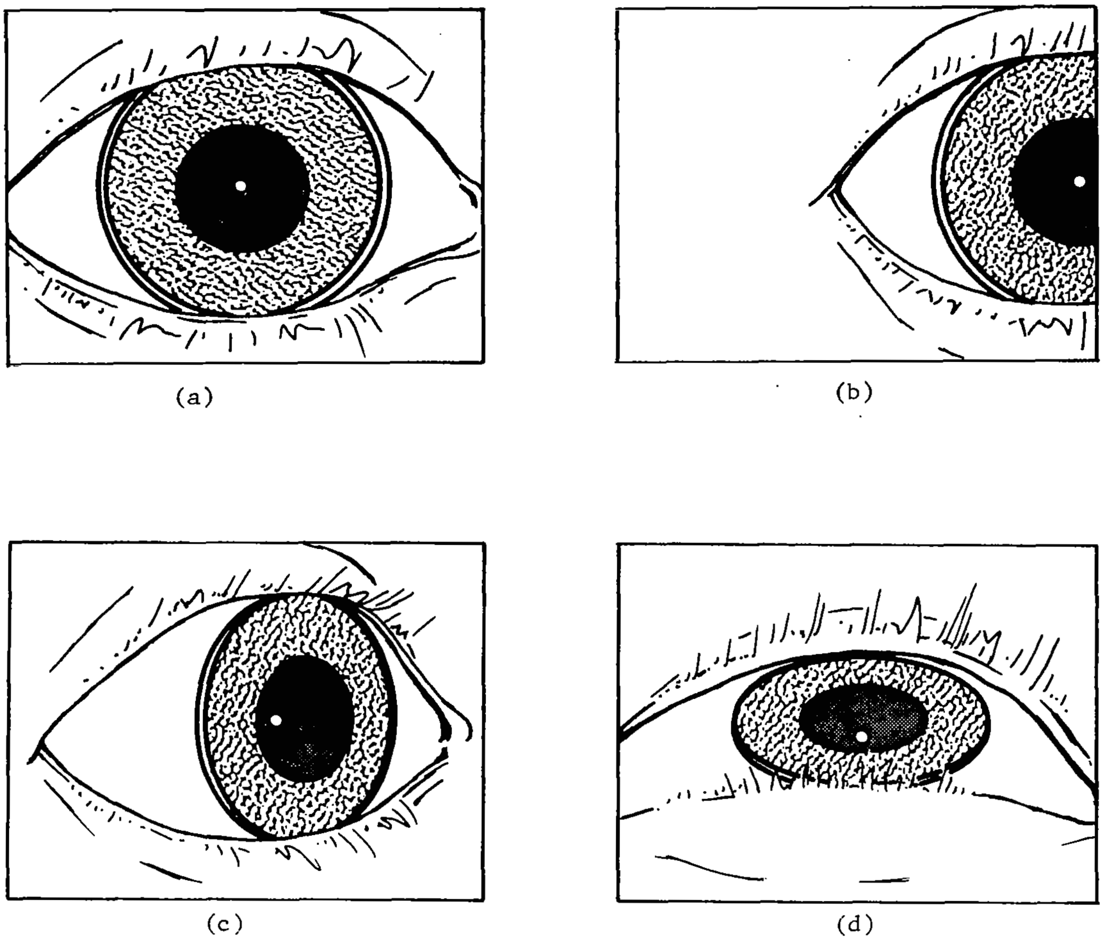
In an electrical technique (EOG), electrodes placed on the skin near the eyes sense small electrical potential proportional to eyeball rotation relative to the skull. (For a summary of eye direction sensing techniques see reference 1.)

The Oculometer Technique

The Oculometer technique for measuring eye direction is based upon the fact that the position of a corneal reflection of an incident collimated beam of radiation, relative to the center of the pupil, is proportional to only the angular direction of the eye (relative to the incident collimated beam). This relative position of the corneal reflection does not depend upon the spatial position of the eye. (See Figure 1). The goemetry of the technique is described in Appendix A.

The Oculometer technique has the important advantage that it allows electro-optical sensing of eye direction without requiring head clamping. In most other optical eye direction sensing techniques-for example tracking the corneal reflection- a lateral displacement of the eye (as for example between Figures 1a and 1b) produces a displacement of the detail being tracked (in this example the corneal reflection) which cannot be distinguished from the displacement of this detail that occurs in a pure rotation (as in Figures 1c and 1d). In this case, therefore, the sensing device must be fixed (usually clamped via a dental bite plate) very firmly to the skull. (Even then the possibility exists of some small unknown variable lateral displacement of the eyeball in its socket). The necessity for rigid clamping is evident from the displacement/eye direction scale factor of these other optical techniques:

> Corneal reflection tracking: Scale factor is about 3×10^{-3} inches per degree
>
> Sclera/Iris tracking: Scale factor is about 8×10^{-3} inches per degree



(a) eye looking straight ahead - note corneal reflection is at center of pupil.

(b) eye looking straight ahead but laterally displaced - note corneal reflection still at center of pupil.

(c) eye looking to the side - corneal reflection displaced horizontally from pupil center

(d) eye looking up - corneal reflection displaced vertically from the pupil center.

Figure 1 OCULOMETER EYE SENSING TECHNIQUE

With the Oculometer sensing principle (Figure 1), lateral displacements of the eye cannot be confused with rotational displacements because they produce different effects. There is, therefore, no requirement for head clamping.

General Description Of Any Oculometer

Any Oculometer (Figure 2) will contain a source of radiation with which to illuminate the eye. (This radiation should be in the near infrared so that it will be invisible and not disturb the subject.) This radiation will be suitably projected, by the Oculometer's projection optics, onto a region of space near the Oculometer, which may be called the eye space. The eye space is also imaged (by the Oculometer's collection optics) onto the screen of an electro-optical sensing device. An electronics system searches for, acquires, and then tracks the pupil/iris boundary and also the corneal reflection of any eye placed in the eye space. Eye direction information is derived by the electronics system as the displacement of a circular scan, tracking the corneal reflection, from a circular scan tracking the pupil/iris boundary.

A laboratory Oculometer has been constructed with a 1.2 in. diameter eye space located a few inches from a dichroic beam splitter that is attached to the Oculometer. (The laboratory Oculometer is described in Appendix B; a more detailed description is given in reference 2.) The subject places his

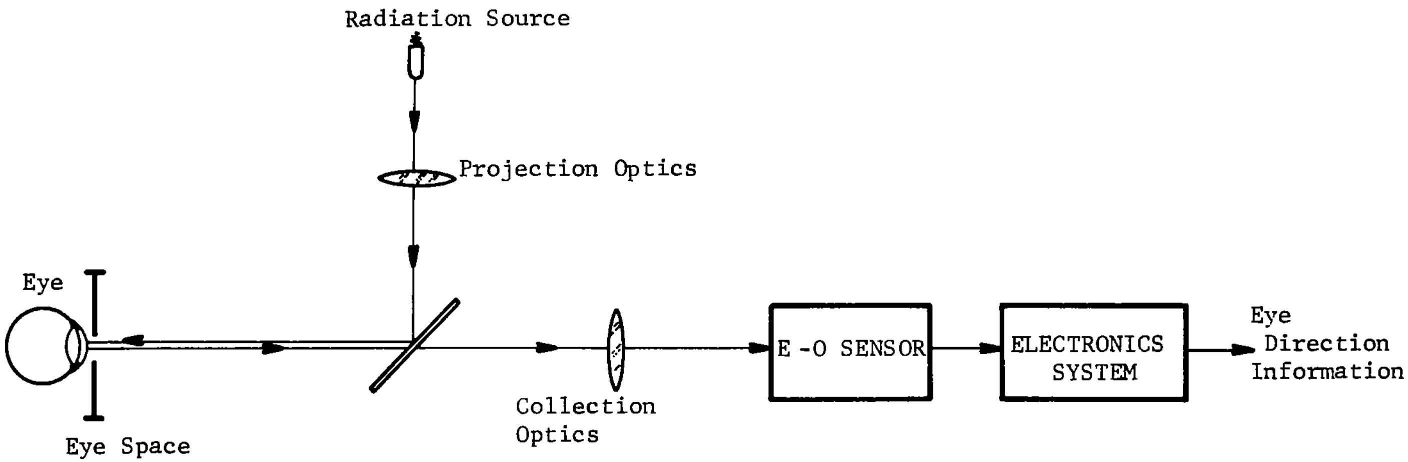


Figure 2 COMPONENTS OF BASIC OCULOMETER SYSTEM

eye close to the dichroic beam splitter (through which he sees normally because it is highly transmitting in the visible band) so that his pupil is within the eye space region (Figure 3). The electro-optical system then acquires and tracks his eye, and eye direction information is generated as described above. (Eye direction is measured relative to the optical axis of the Oculometer.)

It is evident, from the basic form of the Oculometer optical system described in reference 2, that the Oculometer need not necessarily be in the form, or configuration, of the laboratory Oculometer shown in Figure 3. The general optical requirements for any Oculometer are simply that (a) a substantially uniform illumination (of invisible IR) be provided, over the eye space region, from a source appearing to subtend about 1 degree at the eye, and having a radiance of about 3 watts/cm^2/steradian, and that (b) The eye space region be imaged onto the screen of a suitable electro-optical sensor by means of an optical system having a collection aperture equal in size, and (optically) coincident with, the illumination source.

In particular, a remote configuration of the Oculometer is possible in which the Oculometer-subject distance can be much larger than in the laboratory Oculometer. For example, with an Oculometer-subject distance of 60 in. the diameter of the aperture

Figure 3 SUBJECT PREPARING TO USE THE LABORATORY OCULOMETER

of the illumination and collection optics will be only of the order of 1 in.; that is, the physical size of the optical elements is not unreasonably large.

One application of the remote Oculometer that is of particular interest is the measurement of the eye direction of a pilot without interfering with his normal activities. The subject of this report is the design of a remote configuration Oculometer suitable for this application.

A number of important parameters of the remote configuration are shown in Figure 4.

1. Eye Space

When the subject is separated from the Oculometer, and not required to look through a relatively small opening (as shown in Figure 3), it is obvious that a larger region of eye space must be provided to allow for 'side to side', 'up and down' and 'in and out' motion of the subject's head relative to the Oculometer. As discussed later, it is, in general, impractical to cover a total eye space volume (as shown in Figure 4) directly, as was the case in the laboratory Oculometer (Figure 3). Instead, only a relatively small instantaneous eye space volume is, at any instant, illumina and then imaged onto the electro-optical sensor. (Note tha now, the eye space region must be considered as a volume rathe

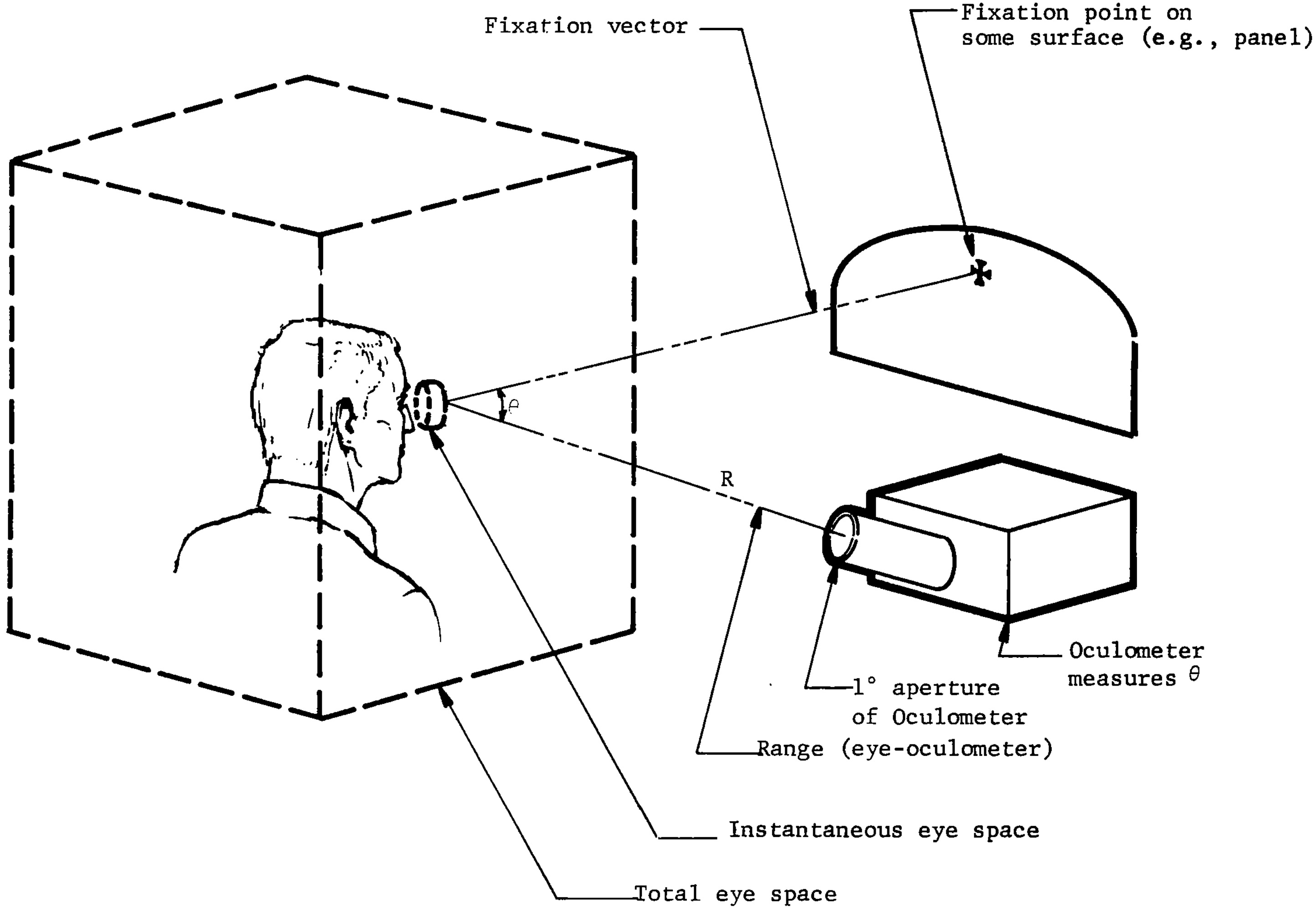


Figure 4 REMOTE CONFIGURATION OF OCULOMETER

than just an area (as implied earlier in the case of the laboratory Oculometer). This is because of the finite depth of focus of the Oculometer Optical System--about ± 1 in. in the case of the laboratory Oculometer--in relation to the range of "in-out" head motion that can be expected to occur in the remote configuration. An optomechanical focusing system and an optomechanical moving mirror system are used, in the remote configuration, to extend (deploy) the instantaneous eye space volume over the total required eye space volume.

2. Measurement

The electronics system of the Oculometer measures the relative displacement of the images of the corneal reflection and of the pupil. In applying this measurement to a computation of eye direction it is clear that the range (R) (from eye to Oculometer) must be known. Moreover, the eye angle θ (Figure 4) that can be computed as

$\theta \propto$ R X (relative corneal reflection/pupil image displacement)

is the angle between the gaze (or fixation) vector and the line joining the Oculometer to the eye. Since, in general, a relatively large amount of head motion will occur (within the total eye space volume) the eye-Oculometer line cannot be considered as a fixed reference axis. Thus to determine the absolute direction of the eye it is necessary to measure the absolute direction of the eye-Oculometer vector, as well as the angle θ.

Finally, it may be noted that the information required from the Oculometer may not be the absolute direction of the gaze vector, but rather the location, on some two-dimensional surface (such as an instrument panel), of the fixation point. As discussed later the position of the fixation point may be determined either by tracking both eyes or by knowing the spatial relationship between the fixation surface and the Oculometer, or by locating a number of reference sources on the fixation surface.

The range of angles (θ) that can be measured is limited-(a) by the requirement that the Oculometer must have an unobstructed view of most of the eye detail to be tracked, and (b) by the requirement that the corneal reflection be formed by a central region of the corneal surface--which is of high optical quality rather than the edge regions where there are large changes of curvature (Restricts θ to about ±30 degrees).

Since, in some cases, the dynamic range of the Oculometer will be limited by item (b) above, consideration should be given to sensing eye direction, in the case of large values of θ, by sensing the apparent eccentricity of the pupil. When the eye is rotated, an oblique view of the nominally circular pupil is obtained and eye direction could be derived from a measure of the pupil eccentricity. This technique is unsuitable for small values of θ because pupil eccentricity is proportional to cos θ and, for small values of θ.

$$\cos \theta \propto 1 - \frac{\theta^2}{2}$$

Thus, when θ is small, the magnitude of the eccentricity of the pupil is very small and impossible to measure accurately. For large values of θ (i.e., θ=30 degrees) the function cos θ is approximately linear with θ. The pupil eccentricity technique can be considered, therefore, for use when the corneal reflection technique fails because of item (b) above.

General Description Of The Remote Oculometer

The guideline specifications, for this study, of the Remote Oculometer are as follows:

The Remote Oculometer should allow tracking of either eye or both eyes of the subject at a distance of 3 to 5 feet over a dynamic range of ±90 degrees minimum left and right and up and down, with allowed head motion of ±6 inches in all directions. The accuracy and precision of the system should be ±1 degree and ±1/2 degree, respectively, within ±20 degrees of the optic axis, with reduced accuracy and precision allowed beyond the central ±20 degree cone. The resolution of the system should be 0.25 degree on the optic axis. The minimum smooth tracking rate should not be less than 60 degrees/s, and the acquisition and response times should be less than 0.1 second.

In order to avoid excessive and confusing generalities, it is appropriate at this point to define the general configuration of the remote Oculometer that will best fit this specification. Reasons for the component, system, and design choices, implicit in this initial description, will be given later. The general remote Oculometer consists of 4 subsystems as illustrated in Figure 5. These are:

1. Head Marker
2. Two-axis moving mirror
3. Eye acquisition and tracking system
4. Electronics

Head Marker

A head marker is included to permit rapid <u>initial</u> acquisition (i.e., within about 0.1 s) and to ensure rapid and reliable regaining of track after any loss of track.

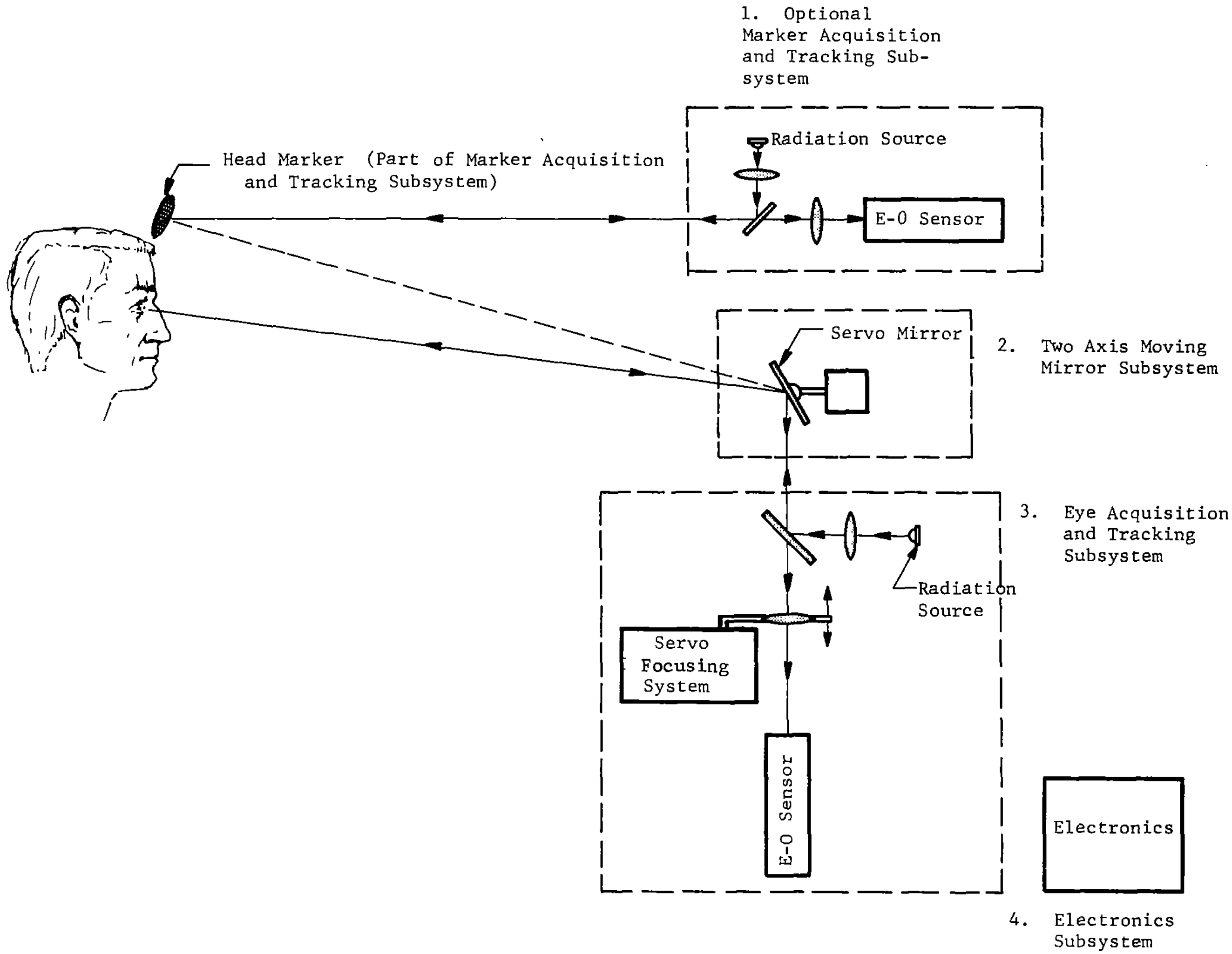


Figure 5 REMOTE OCULOMETER SUBSYSTEMS

It consists of a special corner reflecting material, approximately 1 in. square, 0.2 in. thick to be located near the eye e.g., fixed to a helmet, head band, or intercom head set etc.

Two-Axis Moving Mirror System

The two-axis moving mirror system consists of a gimbal mounted mirror capable of two-axis rotation (about its center). The mirror is rotated by two torque motors and the mirror deflection is measured by two rotary variable differential transformers. Depending upon its mode of operation, the mirror may be commanded to move to a given angular position (or positions) or may be a part of the eye acquisition and tracking subsystem.

The primary function of the two-axis moving mirror subsystem is to deploy the relatively small instantaneous field of view of the eye acquisition and tracking subsystem, (i.e., instantaneous eye space) over the total eye space area.

It serves specifically to:

1) direct the instantaneous field of view of the eye tracking subsystem to the head marker.

2) deflect this instantaneous field of view from the head marker to the eye

3) maintain the instantaneous field of view over the eye

4) deploy the instantaneous field of view from one eye to the other (if desired)

As soon as the head marker is acquired by the eye track system, approximate range (from eye to Oculometer) information becomes available from an automatic focus system that will cause the photocathode image of the head marker to become sharply focused. This range information defines the approximate bearing of the eye, relative to the marker, as seen by the eye tracking system. Thus the mirror can be commanded to deploy the instantaneous eye space area approximately over the eye. If the instantaneous field of view is made large enough, to allow for the inevitable uncertainties of position in this process, the eye will then be within the instantaneous field of view and can then be found by a purely electronic search; that is, without any search motion on the part of the mirror.

Eye Acquisition And Tracking Subsystem This system consists of:

--a xenon short arc lamp source of invisible (or slightly visible) infrared radiation

--a projection optical system to illuminate a relatively small instantaneous eye space

--A collection optical system to image the instantaneous eye space onto the screen of the E-O sensor

--An automatic focusing system for the collection optics. This can either be commanded (to a given focus setting) by an external signal or can automatically focus an image by a dither motion of the focusing lens

--An E-O sensor (an image dissector or an image intensifier/ image dissector combination)

As described above, the instantaneous field of view (instantaneous eye space) of this system is deployed, in various ways, by the moving mirror. The following are the corresponding modes of operation of the eye acquisition and tracking system:

1) Head marker search

   The moving mirror is made to execute a raster search motion in which the instantaneous eye space is scanned over the total eye space in a search for the relatively large, highly reflecting, marker.

2) Head marker track

   The head marker is briefly tracked during the time it takes for the autofocusing system to servo itself into a fine-focus position.

3) Eye Search

   This mode is similar to the search mode of the laboratory Oculometer as described in Appendix B

4) Eye track

   This mode is similar to the eye track mode of the laboratory Oculometer as described in Appendix B

(An optical all-electronic head marker search and track system could be added to the system outlined above for situations where very high speed acquisition and reacquisition are of over-riding importance. It would involve additional panel mounted instrumentation as indicated in Figure 5)

ELECTRONICS SYSTEM

The electronics system processes the video signal generated by the image dissector, generates scan deflection, focus control, and mirror control signals, and computes eye direction.

SYSTEM FACTORS

This section is devoted to consideration of the following basic factors:

1. The visibility of the eye to the Oculometer.

2. Derivation of useful information (i.e., eye direction or fixation point position on an instrument panel) from the basic outputs from the electronics system

3. Potential error sources: i.e.,
   --Range measurement errors
   --Mirror angle pick-off errors
   --head roll
   --errors derived from physiological factors of the eye
   --eye tracking errors

Visibility Of The Eye To The Oculometer

Description of Experiments The range of angular eye directions that can be measured by one Oculometer is limited by the requirement that the Oculometer must have an unobstructed view of the eye.

To investigate the typical coverage allowable, the eyes of three subjects were examined from a distance of 20 feet through a telescope upon which was mounted a microscope illuminator. The visibility of the pupil and the visibility of the corneal highlight was then studied as the subject varied his direction of regard. Visibility profile curves were obtained (See Figure 6).

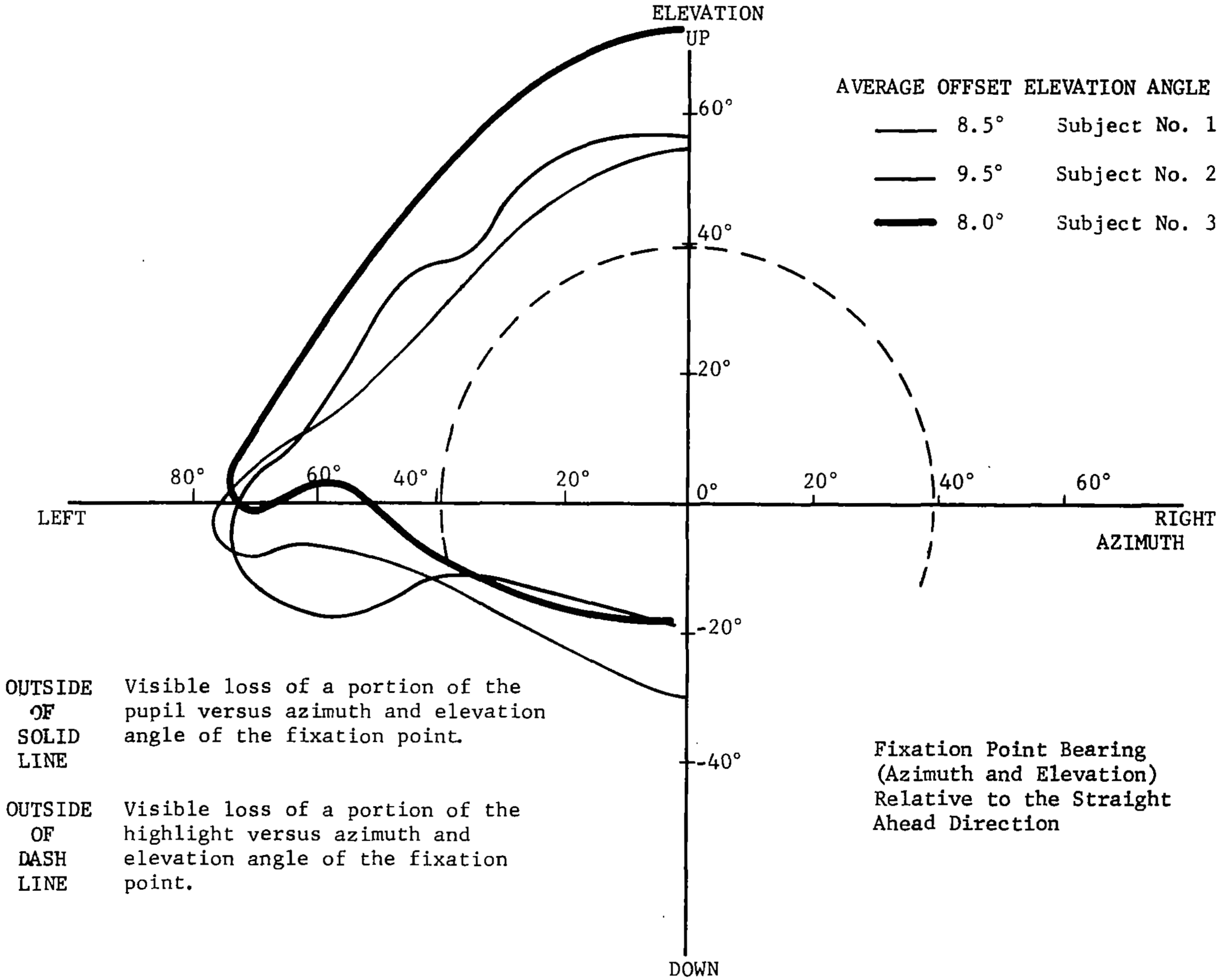


Figure 6 EYE VISIBILITY AS A FUNCTION OF FIXATION POINT BEARING.

These curves show that there is an optimum direction relative to the fixation field from which the Oculometer should look at the eye in order to provide the greatest possible elevation and depression coverage. The profile curves are based upon the selection of the eye having minimum visibility at any bearing. The results of the test are as follows.

Experimental Results The optimum look angle for the Oculometer is 25 degrees in elevation. That is, radiation should be directed at the pupil and recollected from a point 25 degrees below the mean elevation of the direction of regard and along the average azimuth bearing of the direction of regard. (Figure 7).

If the direction of regard (θ), (referenced to the eye-Oculometer axis) exceeds 35 degrees, eye direction information cannot be obtained by monitoring the difference between the pupil centroid and the corneal highlight. At these large angles, any highlight would be generated by the sclera. Therefore, if θ exceeds 35 degrees, it would become necessary to utilize a second measuring technique. At these large eye angles, a measurement of the eccentricity of the pupil (as discussed later) can provide approximate eye direction information. This pupil eccentricity technique is available for values of θ up to the limit set by the obscuration of the pupil by facial details; that is, up to ±70 degrees in azimuth and -35 degrees to +55 degrees in elevation as shown in Figure 7.

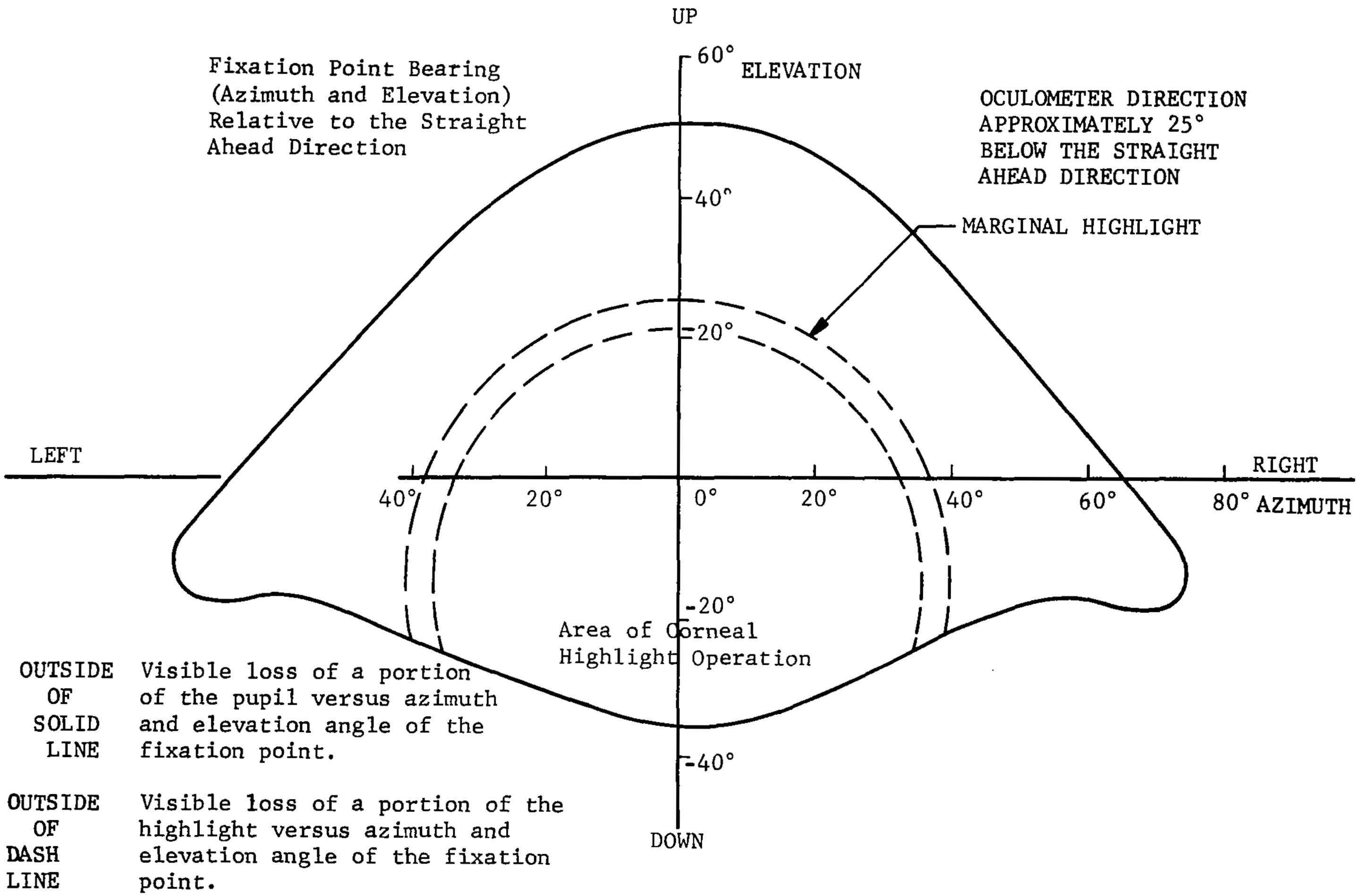


Figure 7 OPTIMIZED EYE VISIBILITY AS A FUNCTION OF FIXATION POINT BEARING

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Thus, inside the azimuth and elevation profile curves of Figure 7 determination of the direction of regard of the eye can be made with a single Oculometer system.

Derivation Of Eye Direction Information

The basic measurement performed by the Oculometer electronics system is of the linear displacement on the sensor photocathode (u,v in Figure 8) of the images of the corneal reflection and pupil center. It is necessary to derive the relationship between this measurement (u,v) and the absolute direction of the eye.

Let $\underset{\sim}{i},\underset{\sim}{j},\underset{\sim}{k}$ be a fixed set of rectangular axes (i.e., aircraft axes), such that when the moving mirror is in the null position (α=0 β=0 in Figure 9) the vectors $\underset{\sim}{i}$ $\underset{\sim}{j}$ are in the plane of the sensor photocathode. As the mirror rotates in azimuth by $\frac{\alpha}{2}$ and then, in elevation, by $\beta/2$ (Figure 9) the "image dissector axes" become rotated relative to fixed space (i.e., relative to $\underset{\sim}{i},\underset{\sim}{j},\underset{\sim}{k}$). The image dissector axes, in the general condition, are shown as $\underset{\sim}{i}_2$ $\underset{\sim}{j}_2,\underset{\sim}{k}_2$ in Figures 8 and 9.

Referring to Figure 8 let K be the displacement of the pupil center from the center of corneal curvature (i.e., K is a constant of the eye). Then it is evident, from Figure 8, that

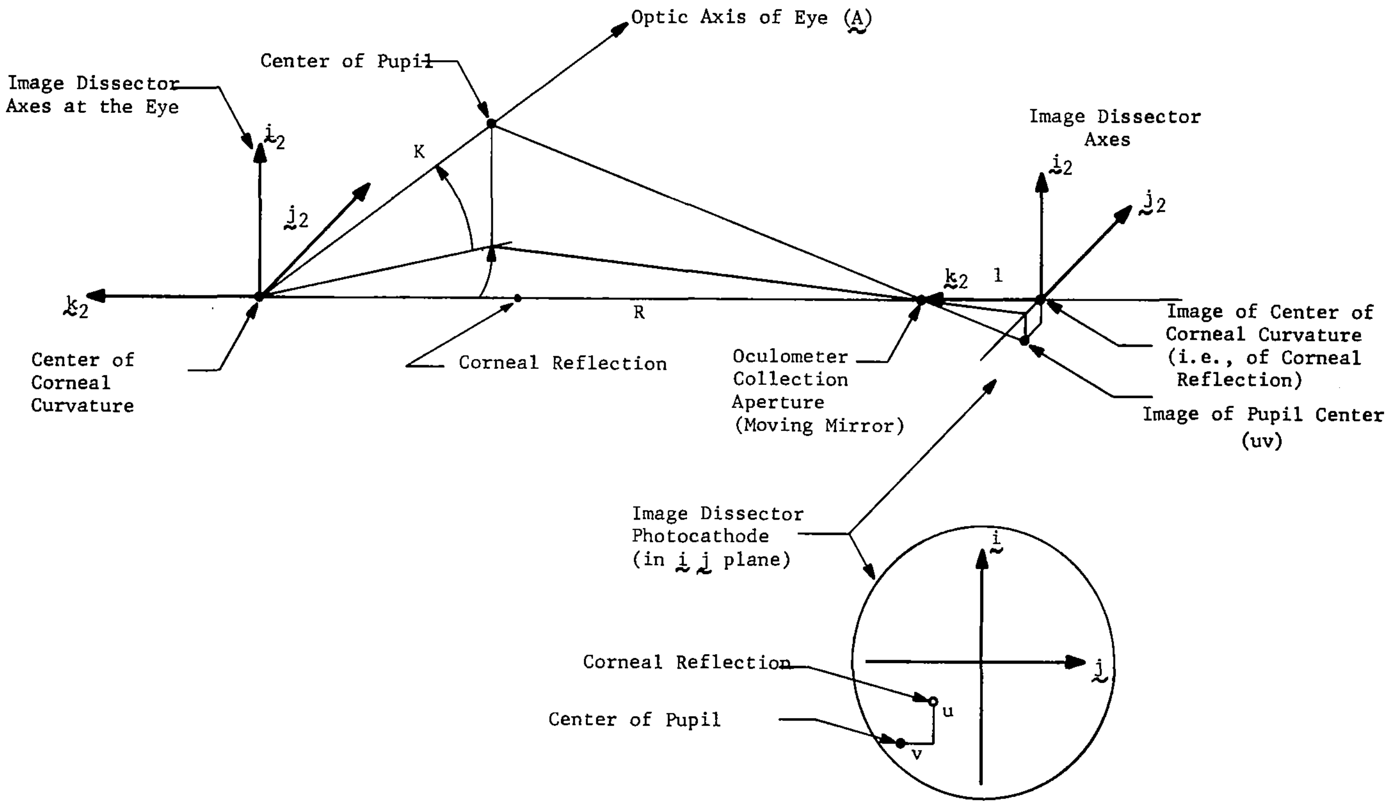


Figure 8 AXIS SYSTEM FOR IMAGING EYE DETAIL ONTO PHOTOCATHODE

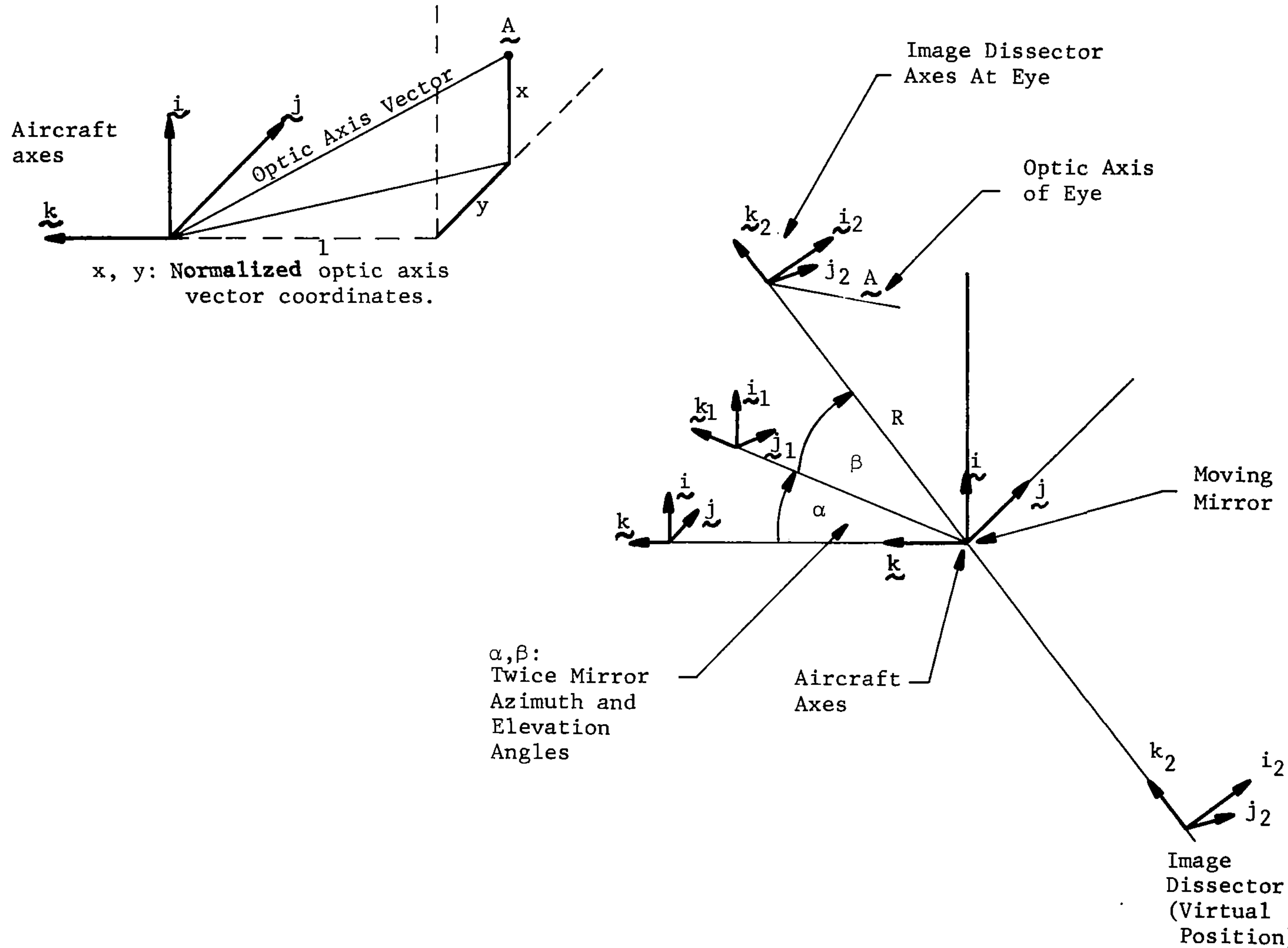


Figure 9 TRANSFERENCE OF IMAGE DISSECTOR AXES TO EYE

$$u = (K/R)\ \underset{\sim}{A} \cdot \underset{\sim}{i}_2$$

$$v = (K/R)\ \underset{\sim}{A} \cdot \underset{\sim}{j}_2 \qquad (1)$$

Where $\underset{\sim}{A}$ is a unit vector along the optical axis of the eye, and R is the range from the eye to Oculometer (See appendix A for a description of the geometrical optics involved in the displacement of the pupil center from the corneal reflection which, in the photocathode image, is the vector $u\ \underset{\sim}{i}_2 + V\ \underset{\sim}{j}_2$)

The vector $\underset{\sim}{A}$ can be defined, in terms of azimuth and elevation parameters (x,y) as

$$\underset{\sim}{A} = \frac{x\ \underset{\sim}{i} + y\ \underset{\sim}{j} \quad \underset{\sim}{k}}{\sqrt{1 + x^2 + y^2}} \qquad (2)$$

(See Figure 9)

In order to derive a relationship between (x,y) (the desired absolute eye direction information relative to fixed axes) and (u,v) (the basic Oculometer measurement) equations (1) and (2) above must be combined. This requires that $\underset{\sim}{i}_2$, $\underset{\sim}{j}_2$ be expressed in terms of $\underset{\sim}{i}$, $\underset{\sim}{j}$, $\underset{\sim}{k}$:

From Figure 9 it is evident that

$$\underset{\sim}{i}_1 = i$$

$$\underset{\sim}{j}_1 = \underset{\sim}{j} \cos\alpha - \underset{\sim}{k} \sin\alpha$$

$$k_1 = k \cos \alpha + j \sin \alpha$$

(where i_1 j_1 k_1 are the "image dissector axes" after a pure azimuth rotation $\frac{\alpha}{2}$ of the mirror)

also,

$$i_2 = i_1 \cos \beta - k_1 \sin \beta$$

$$j_2 = i_1$$

$$k_2 = k_1 \cos \beta + i_1 \sin \beta$$

$$\therefore \quad i_2 = i \cos \beta - (k \cos \alpha + j \sin \alpha) \sin \beta$$

$$j_2 = j \cos \alpha - k \sin \alpha$$

$$k_2 = (k \cos \alpha + j \sin \alpha) \cos \beta + i \sin \beta$$

i.e.,

$$\left.\begin{aligned} i_2 &= i \cos \beta - j \sin \alpha \sin \beta - k \cos \alpha \sin \beta \\ j_2 &= j \cos \alpha - k \sin \alpha \\ k_2 &= i \sin \beta + j \sin \alpha \cos \beta + k \cos \alpha \cos \beta \end{aligned}\right\} \quad (3)$$

Substituting in equation (1) from (2) and (3):

$$u = \frac{K}{R\sqrt{1 + x^2 + y^2}} \left\{ x \cos \beta - y \sin \alpha \sin \beta + \cos \alpha \sin \beta \right\}$$

$$v = \frac{K}{R\sqrt{1 + x^2 + y^2}} \left\{ y \cos \alpha + \sin \alpha \right\} \qquad (4)$$

Given (u,v) (α,β) and R (measurements), and K (constant of the eye), these equations enable the absolute direction (x,y) of the eye to be computed. A first approximation is

$$x = \frac{Ru}{K} - \beta$$

$$y = \frac{Rv}{K} - \alpha \qquad (5)$$

For a one square foot total eye space region, at a minimum range (R) of 3 feet, the values of (α,β) are limited to approximately ±10 degrees. The order of magnitude of the errors involved in the approximation given above are shown below for these maximum values of (α,β) (i.e., worst case).

(cosine = 1): error = 1.5% of (x,y) or 0.3 degree maximum for x, y <20 degrees

(sine = angle): error = .05 degree

$(y \sin \alpha \sin \beta = 0)$: error is 3% of y or 0.6 degree maximum for $x,y \leq 20$ degrees

$(\sqrt{1 + x^2 + y^2} = 1)$: error is ±10% of (x,y) or 2 degree maximum for $x,y \leq 20$ degrees

The approximation

$$x' \doteq \sqrt{1 + x^2 + y^2}\ \frac{R}{K}\ (u + a\ \beta\ v) + \beta\ (1 + \alpha^2/2)$$

$$y' \doteq \sqrt{1 + x^2 + y^2}\ \frac{R}{K}\ v + \alpha \qquad (6)$$

where x, y are given by equation (5) is much better.

The required eye information may, however, not be the absolute direction of the eye (x,y) but rather the location, on some surface, of the fixation point of the eye.

Let (X,Y) be the coordinates of the pilot's fixation point on a plane (π) normal to k and containing the Oculometer moving mirror (Figure 10). Then, from the figure,

$$X = R\ (\sin\beta - x \cos\beta \cos\alpha)$$

$$Y = R\ (\cos\beta \sin\alpha - y \cos\beta \cos\alpha)$$

or, to a first approximation

$$X = R\ (\beta + x) = \frac{R^2 u}{K}$$

$$Y = R\ (\alpha + y) = \frac{R^2 v}{K}$$

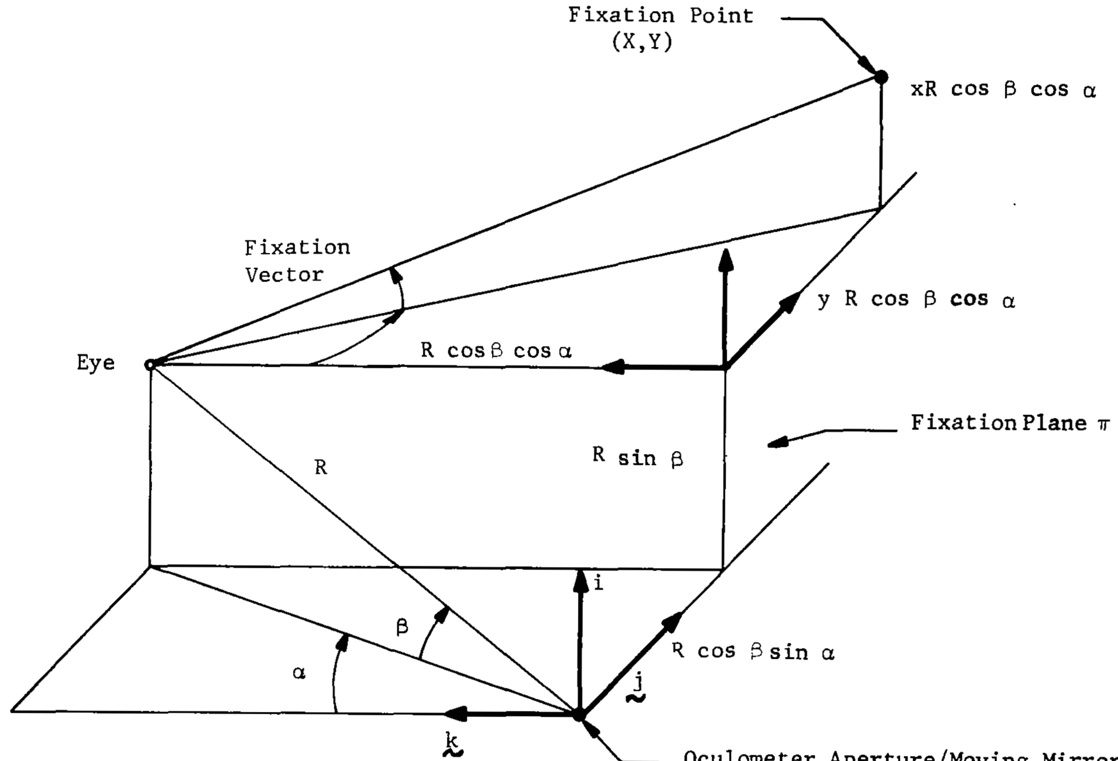


Figure 10 REMOTE OCULOMETER: MEASUREMENT GEOMETRY

In general, the fixation surface (e.g., an instrument panel) will not take the form of an ideal plane, π, as assumed here. The determination of the exact location of the fixation point on a general surface will entail additional computation in which the characteristics of the surface are constants to be programmed into the computation.

This analysis has illustrated how any particular eye information (direction, location of fixation point) can be computed, given:

u,v, (basic Oculometer measurement)
(α,β) (mirror double angles)
R (range from eye to Oculometer) (derived from focus system)

The exact formulae involved are sufficiently complicated as to require special computational equipment (small analog or digital computer). However, simple approximations are available which can yield moderate accuracy without special computation.

The accuracy with which the above parameters must be measured to give an error of 0.1 degree (in x,y) (due to each parameter) or 0.1 in. (in X,Y) is given below for R (nominal) = 60 in. and K (nominal) = .18 in.

α, B: 0.1 degree

u, v: 0.3 thousandths of an inch

R: 0.3% (for x = 30 degrees) for a 0.1 degree error in x (or 0.15% for a 0.1 in. error in X)

An alternative method of deriving fixation point information is to locate a number of suitable IR sources on the instrument panel (as panel markers) and track the corneal reflections of these sources. The Oculometer output with this approach could be a video display of the panel marker reflections, referred to the center of the pupil (Figure 11).

As discussed later the Oculometer system will have a very narrow operating spectral band, and use a xenon short arc lamp for eye illumination if the maximum sun discrimination capability is required. In this event, filament lamps used as panel markers would yield a corneal reflection 100 times less bright than that of the Oculometer source, or about twice the brightness of the average pupil signal. The corneal reflection of the panel marker would also be very small. For example, a .060 in. square filament used as a panel marker source would yield a corneal reflection about 0.3 thousandths of an inch --i.e., about 100 times smaller in area than that of the main Oculometer corneal reflection.

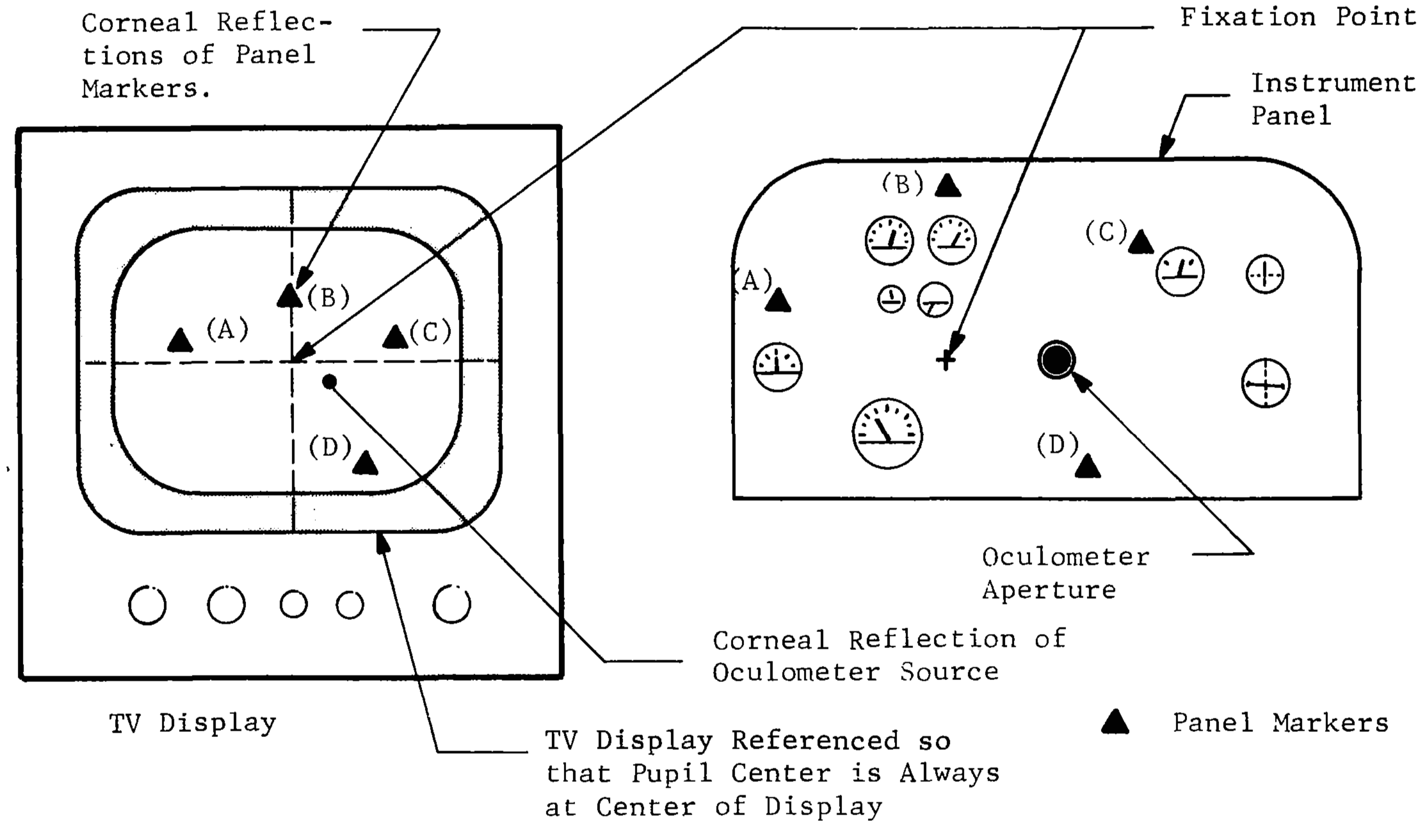


Figure 11 PANEL MARKER SYSTEM

A GaAs diode sublaser as the panel marker source would yield a stronger signal which could be modulated. The maximum radiance of a Texas Instrument GaAs diode OSX 1208 is about 1 watt/cm^2/ steradian. The diode has an effective emitting diameter of 0.072 in. and would, therefore, give a marker corneal reflection about 510 times that of a filament lamp. This would yield a video level about equal to the pupil video level.

If high sunlight discriminating capability is not required, the operating spectral band of the Oculometer can be opened up and a filament lamp panel marker would then give an adequate signal

It is concluded that panel markers could be used to reference the eye fixation point on the panel directly (as illustrated in Figure 11). However, owing to the weak corneal signal that they will generate, the accuracy of location obtainable may (because of tracking noise) be up to about 3 times poorer than that of the basic Oculometer.

Potential Error Sources

The effect of errors in the measurement of range (R), mirror angles (α,β), and eye detail position (u,v) have been discussed in the previous section.

Eye Errors

The following section will analyze the type of eye errors generated by physiological changes which produce an apparent shift in the direction of regard of the viewer.

The Nonfixation Stare The error of a nonfixation stare is due to the inability of the Oculometer; when imaging only one eye, to determine if the range of fixation is a real point on the instrument panel or an imaginary point in space.

If the foveal gaze vector of one of the pilot's eyes intercepts the panel at a point θ and the Oculometer is measuring that eye, then the system will indicate that the pilot is in fact looking at the point θ. He may, however, be staring at infinity "nonfixation stare."

To determine if the subject is not fixating on an object in the near field the convergence of both eyes could be measured. This technique could be used for near field targets that create more then 1/2 degree convergence between the two eyes (i.e., targets less than 20 ft away from the eye).

Pupil Diameter Changes The possibility exists of errors caused by a displacement of the pupil center associated with pupil diameter changes. These displacements may have the following components

a) completely random, i.e., cannot be calibrated out

b) nonrandom (displacements of equal and opposite magnitude for the two eyes) (could be caused by optical aberrations and the asymmetry, in the horizontal direction, of the two eyes). These effects could be cancelled by monitoring both eyes and averaging.

c) other x and y displacements of the pupil center that are repeatable functions of pupil diameter.

Effects (b) and (c) could be compensated for automatically since pupil diameter information is available in the Oculometer.

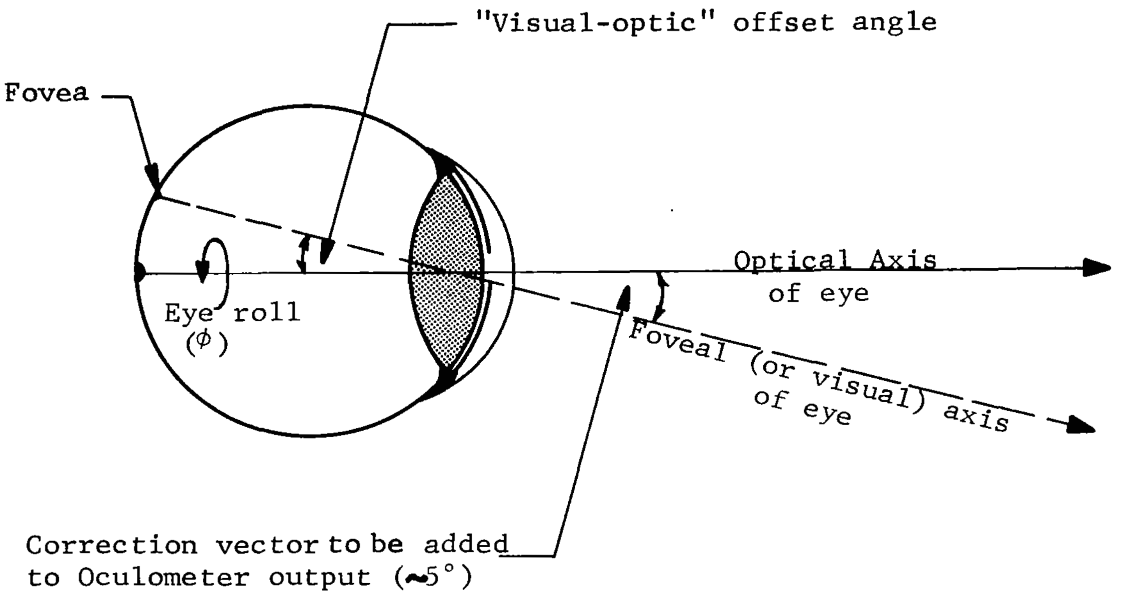
Based upon operating experience with the laboratory Oculometer, pupil diameter effects appear to be negligible for the minor pupil diameter fluctuations that occur in a constant ambient illumination. Nonrandom effects with larger pupil diameter changes have been observed, but it has not been established that these are real effects. They may be due to the large pupil signal variations associated with large pupil diameter changes, and system limitations of the laboratory Oculometer in the present form.

The Effect Of Head Roll The Oculometer senses the angle between the optical axis of the eye and the Oculometer direction. In order to correctly measure the angle between the visual axis of the eye and the Oculometer direction, the "visual-optic" offset angle must be added to the Oculometer output. This fixed angle addition is valid provided the eye is not rotated about the optic axis (See Figure 12).

Eyeball roll occurs in natural eye motion (mostly according to Listings law (Refs 3,4,5) so that the small "errors" introduced are repeatable and are to be considered as part of the non-linearities associated with the measurement technique), and also with head roll. (See Appendix C)

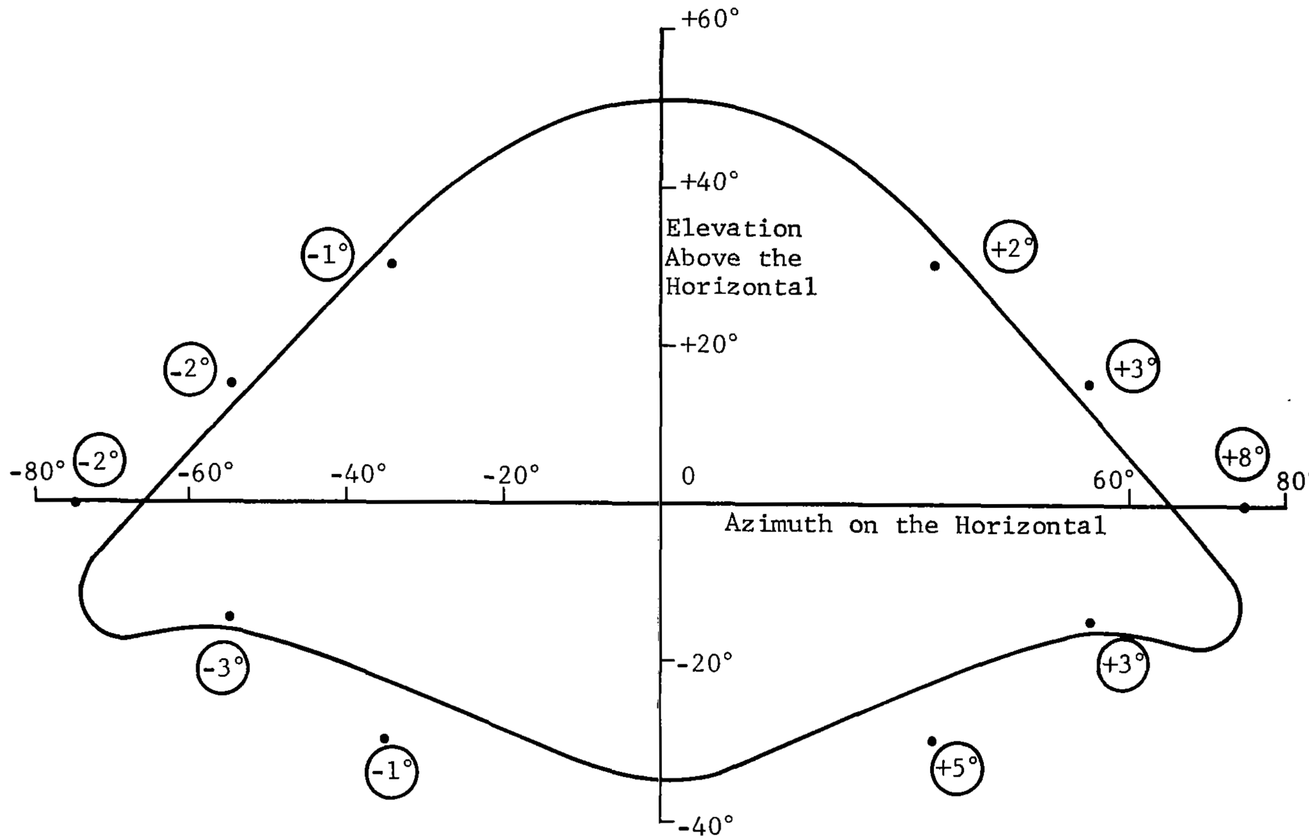
Direct visual studies of the eye during head rotation about the visual axis, at about a 45 degree/s rotation rate, indicate that the eyes are stabilized to the space coordinate system for head roll angles less then ±7 degrees: the speed of rotation and magnitude of the roll angle seemed to establish the size and frequency of discrete roll steps that the eye undergoes. For natural target studies within the profile curves generated in Figure 13, the head roll angles, on the average, do not exceed ±7 degrees as indicated. However, the head can be rolled as much as ±40 degrees and conditions of this nature might exist for a pilot maneuvering a high speed aircraft.

If a head roll angle greater than ±7 degrees occurs, then in an Oculometer system monitoring only one eye, an error will be introduced.



The correction vector that has to be added to the eye is a function of the roll angle of the eyeball: correction vector (4° horizontal + 1° vertical)$e^{i\phi}$ where ϕ is the roll angle of the eyeball.

Figure 12 VISUAL-OPTIC OFFSET ANGLE



Natural Head Roll Angles
For Points on the Masking
Profile Curve. HEAD ROLL
ANGLES ENCIRCLED.

Figure 13 HEAD ROLL PROFILE

The best way to overcome at least most of the adverse effects of head roll is to monitor both eyes. This technique utilizes the equal and opposite horizontal offset appearing in the two eyes (See Figure 14). The average of the direction of regard angles measured directly by the Oculometer on both eyes is thus a direct measure of the line of regard of the observer in the horizontal plane. The offset angle in the vertical plane is ≈1 degree, therefore, even if a maximum 40 degree head rotation occurred, this would yield a vertical error of only 0.75 degree.

BASIC DESIGN FACTORS

Eye Safety

Eye damage could occur with the Oculometer because of:

a) excessive irradiance at the front surface of the eye

or b) excessive irradiance of the retina.

Effect (a) is a function of the irradiance level (watts/cm^2) at the eye, of the Oculometer radiation, while effect (b) is a function of the radiance of the source (watts/cm^2/steradian).

The nominal source radiance of the laboratory Oculometer was 1.5 watts/cm^2/steradian. With f/50 illumination optics this

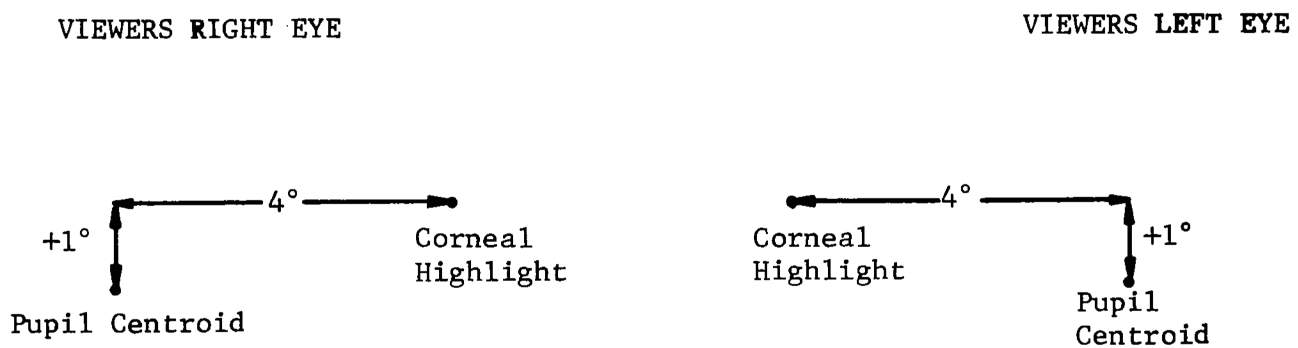

VIEWERS RIGHT EYE
VIEWERS LEFT EYE
4°
+1°
Corneal Highlight
Pupil Centroid
4°
Corneal Highlight
+1°
Pupil Centroid

Figure 14

yields an eye space irradiance of 600 $\mu W/cm^2$. The total solar irradiance at the earth's surface (with an air mass of 2) over the spectral range 0.4 to 1.0μ is about 53 mW/cm^2. Thus from the point of view of corneal irradiance, the radiation level of the laboratory Oculometer is about 100 times less than that due to natural solar radiation, and is therefore, obviously well within the safe level.

The source of illuminating radiation in the Oculometer will subtend an angle of approximately 1 degree at the eye. The retinal image of the radiation source will, therefore, be about 0.5mm in diameter.

The threshold retinal irradiance (and threshold exposure), for retinal injury with an image of this size on a rabbit retina, is shown in Figure 15, according to Ham (Reference 6) and Alexander (Reference 7). Also shown is the maximum continuous irradiance level that will not cause permanent damage as given by O. Pomerantzeff of the Retina Foundation. (This is 0.75 $cal/cm^2/s$ or 3 $watts/cm^2$). A safety factor of 20 will be applied to this last value. This yields a maximum safe operating retinal irradiance of 0.15 $watts/cm^2$. (Also shown in Figure 15)

The corresponding apparent source radiance ($B_s t_I$) is then given by:

$$0.15 = \left(\frac{d}{a}\right)^2 (B_s t_I) \, \pi/4 \quad \tau$$

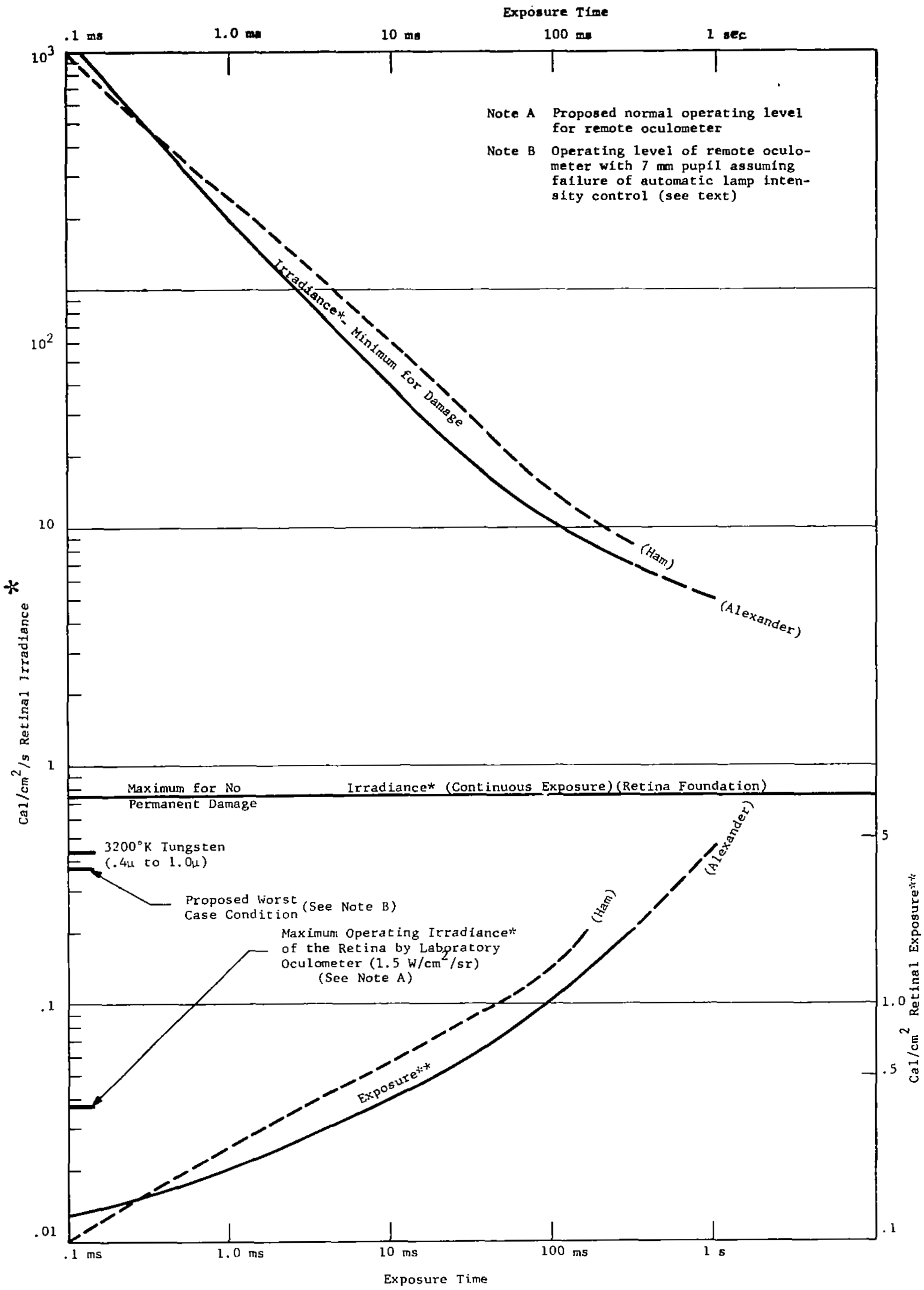


Figure 15 RETINAL SAFETY DATA

where τ is the transmission factor of the ocular media, d the pupil diameter, and a, the focal length of the eye.

As an additional safety factor, the value of τ will, for this calculation, be assumed to be unity. The value of "a" will be taken as 23mm.

This gives $B_s t_I \approx \frac{100}{d^2}$

This function is plotted in Figure 16.

It is clear that an apparent source radiance of 1.5 watts per cm^2 per steradian will satisfy the safety criterion, that has been specified above, under all conditions. However, for bright scenes the pupil diameter will almost always be about 3mm or less. From Figure 16 it can be seen that an apparent source brightness of 10 watts/cm^2/ steradian, or more, is then permissible. It is shown elsewhere that the intensity of the pupil signal detected by the Oculometer is inversely proportional to the square of the pupil diameter. Thus when the pupil diameter is small, a higher source radiance would be useful to overcome the effect of a lower return from the eye. This suggests that it might be desirable to control the source radiance by a measure of the scene luminance.

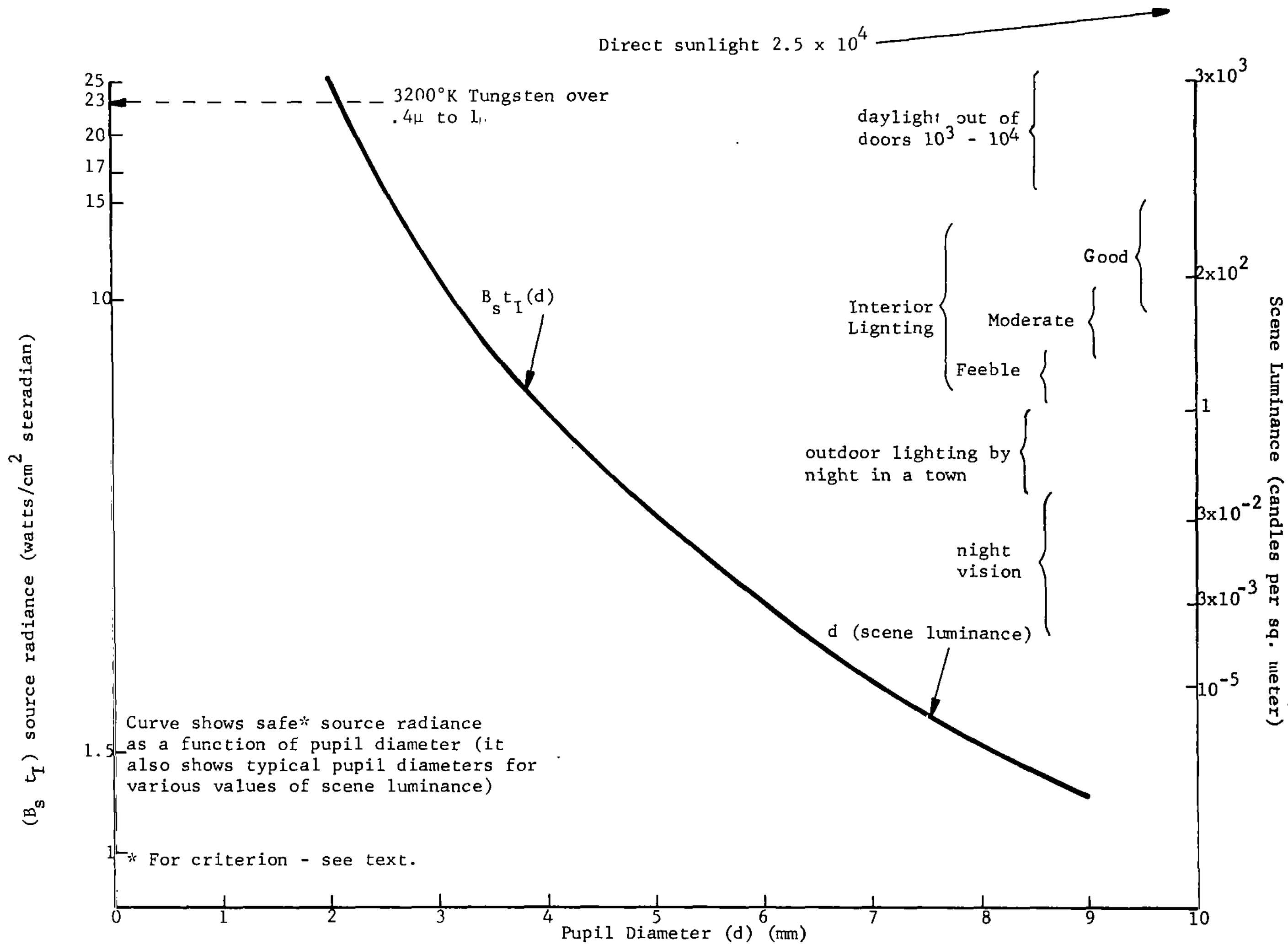


Figure 16 MAXIMUM SAFE OPERATING APPARENT SOURCE RADIANCE ($B_s t_I$)

Assuming that the pupil diameter will always vary with scene luminance, as shown in Figure 16, it would then be possible to arrange that the source radiance was always as high as possible, consistent with the safety requirement as specified in Figure 16. However, there is no absolute guarantee that the pupil diameter will vary with scene luminance, as indicated in Figure 16. Some subjects are observed to have unusually large pupils in relation to the ambient scene illumination. Another possible technique, to permit the use of the highest possible source radiance, would be to control the source intensity by a measure of pupil diameter, as determined by the Oculometer (either directly or by sensing the pupil signal-which is inversely proportional to pupil diameter). This approach cannot, again, be considered as providing an absolute guarantee that the safety criteria will not be exceeded, because of possible Oculometer malfunctions leading to an incorrect estimate of pupil diameter.

In order to place these considerations in perspective, it is to be noted that the tungsten filament, at 3200°K, has a radiance, integrated over the band 0.4 to 1.0μ, of about 23 watts/cm^2/steradian. Allowing for the variation of the transmission factor of the eye over this spectral band, the equivalent source radiance, at 0.85μ, is 17 watts/cm^2/steradian. Short exposures (e.g., 1 s) to such a source are not considered dangerous. (Long foveal exposures would not normally occur because of the discomfort in viewing a visible source, of this intensity, for prolonged periods.)

It is concluded that the operating level of the Oculometer source radiance can be increased safely to 15 watts/cm^2/steradian, for small pupils. (This latter qualification is, according to the threshold safety data given in Figure 15, not necessary. However, it seems prudent to adhere to it in order to reduce the probability of any injury to an infinitesimal value). This control of the source intensity should be based upon maintaining the magnitude of the pupil signal received by the Oculometer at a constant value. This ensures that the retinal irradiance is kept constant. (The source radiance would nominally be a maximum of 15 watts/cm^2/steradian at a pupil diameter of 2.5mm (or less) falling to a minimum of 1.5 watts/cm^2/steradian at the largest pupil diameter.)

The "Bright Pupil" Illumination Technique

This technique is described in detail in Reference 2. It involves the formation of an image, on the retina, of the IR source that illuminates the eye of the subject. Some of the IR radiation falling onto this retinal image of the source is reflected back, and some of this reflected radiation passes through the eye pupil/lens and is thereby reflected back onto the source. A beam splitter in the Oculometer system allows some of this returned radiation to be collected by a lens system which images the pupil onto the sensor screen.

There are two important performance characteristics of the bright pupil system:

1) the absolute intensity of the pupil image formed at the sensor screen
2) The contrast between the pupil detail and the rest of the eye and head.

These characteristics depend on

a) The reflection factor (K_τ) of the retina and the transmission factor (τ) of the eye

b) the sharpness (i.e., degree of focus) of the source image that is formed on the retina

c) the sharpness (i.e., degree of focus) of the retinal image that is formed at the effective collection aperture of the Oculometer (See Figure 17).

In previous work (Reference 2) the effective reflection factor of the retina, including the transmission loss in the eye, (i.e., $K_\tau \tau^2$) was measured and found to be in the range 0.014 to 0.030.

The effective reflection factor of the pupil is, according to simple theory, given by

$$R = (K_\tau \tau^2) \left(\frac{d}{a}\right)^2 F^2$$

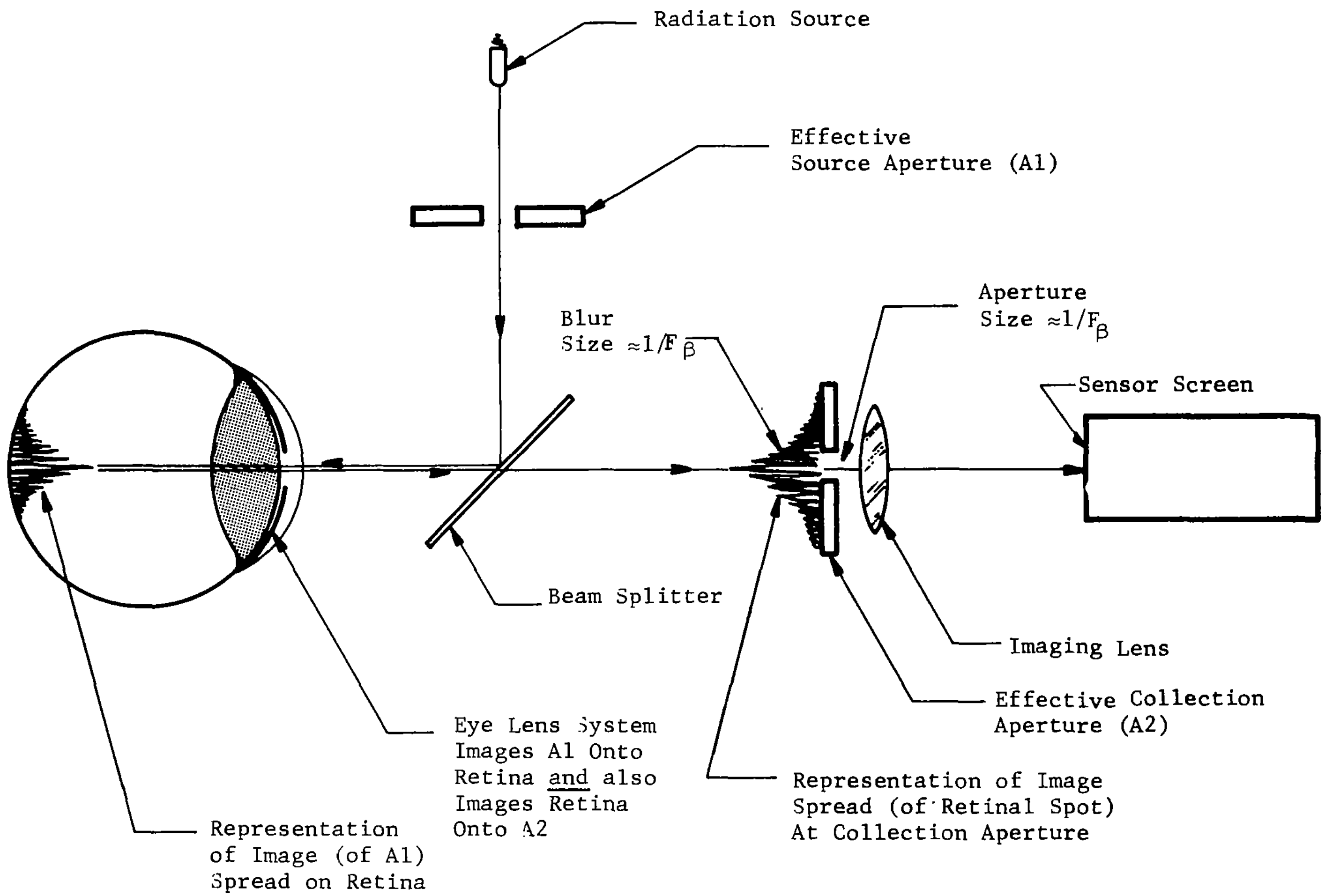


Figure 17 FINITE FOCUSING ACCURACY OF EYE IN BRIGHT PUPIL TECHNIQUE

where d is the diameter of the eye

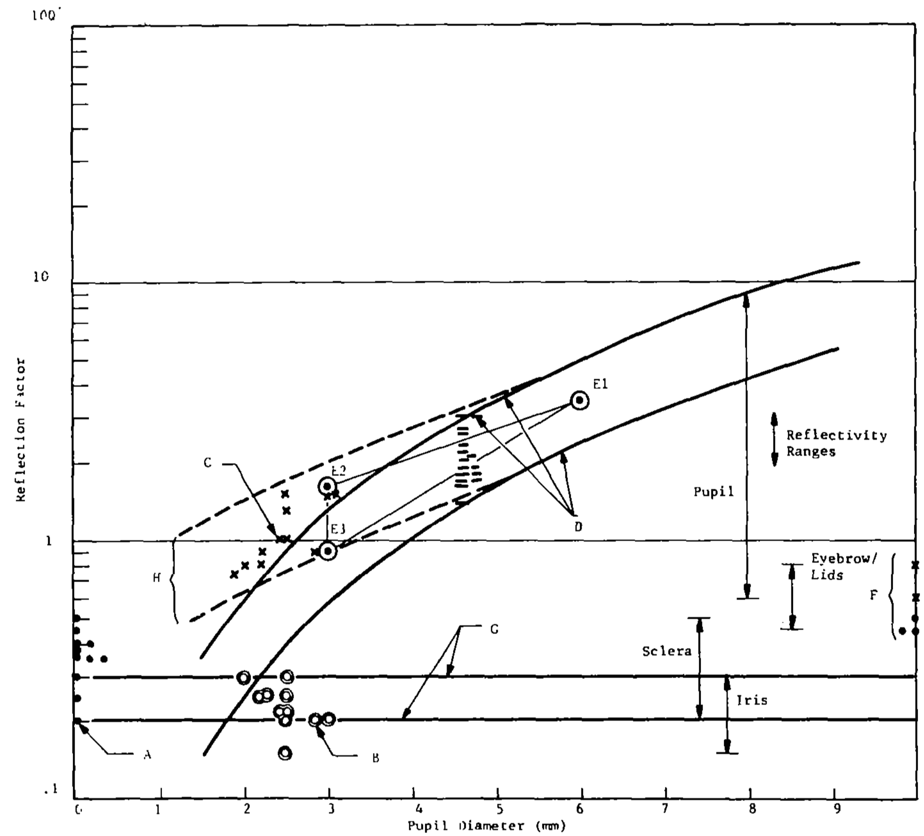
a is the focal length of the eye

and F is the Oculometer F/number (i.e., the reciprocal of the angle subtended at the eye by the common source collection aperture.)

The measured reflectivities of the pupil, iris, sclera, eyelids, and eyebrows of a number of subjects are plotted in Figure 18. The pupil reflectivity is shown (solid lines, D) as a function of pupil diameter by extrapolation according to simple theory from measurements of the retinal reflectivity of a number of subjects. These measurements were made with a relatively large pupil. As indicated in the figure, additional measurements were made of pupil reflectivity with a small pupil. These additional measurements show that the actual small pupil reflectivity is higher than that predicted by simple theory. A specific test of one subject showed that the 3mm reflectivity was about twice that predicted by simple theory from the 6mm reflectivity (E, in Figure 18).

In simple theory, it is assumed that the eye lens is perfect and all images of the Oculometer source are perfectly sharp. The deviations from this assumption will now be considered.

A photograph was taken of the retinal image, as formed at the collection aperture (A2 in Figure 17), with an F/50 illumination system.



A ● Sclera Reflectance 8-2-68

B ◎ Iris Reflectance 8-2-68

C ✖ Pupil Reflectance 8-2-68 (as function of pupil diameter)

D ▬ Pupil Reflectance Computed as Function of Pupil Diameter (Solid Line) From Measured $-2K_R$ Values (Line Segments) March 1967 Monthly Progress Report Contract NAS 12-531

E ⊙ E1 Measured Pupil Reflectance at 6 mm Diameter } 7-25-68

E2 Measured Pupil Reflectance at 3 mm Diameter } 7-25-68

E3 Value of E2 Predicted From E1 by Simple Theory

F ● Eyelid Reflectance } 8-2-68

✖ Eyebrow Reflectance } 8-2-68

G Range of Iris Reflectance 1-10-67

H Adjustment in D to Allow for Results C and E

NB (1) Dates given are dates of written reports of the indicated measurements.

(2) Bright pupil system F/number: 50.

Figure 18 EYE REFLECTIVITY DATA .8μ ± .1μ

It showed

a) the source, sharply imaged to at least a 0.1 degree blur circle

and

b) A large superimposed diffuse background, approximately 25% of the peak image intensity, and extending over a region of about ±20 degrees. This suggests that there is actually 4 times more available energy in the retinal return that is actually picked up with an F/50 optical system.

It is believed that the large background patch (b above) is due to some form of scattering of the incident retinal radiation. In addition to this effect there will also be a defocusing of the source image when the eye lens is incorrectly focused. This effect will now be considered.

Let the relaxed posterior focal length of the eye be f. Consider the case when the eye is then accommodated to a focus point R in front of the eye (Figure 19). The accommodated focal length is x, where

$$1/f + 1/R = 1/x$$

$$\therefore \quad x = fR/(R + f)$$

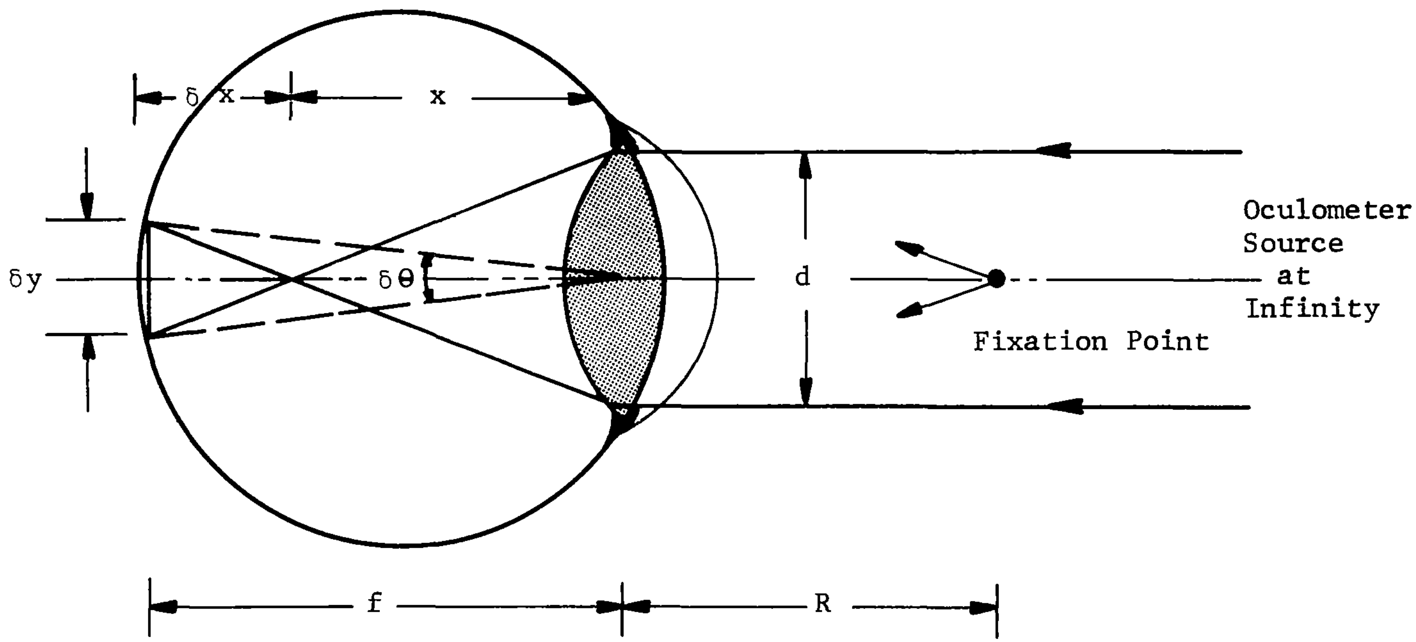


Figure 19 MAXIMUM ACCOMMODATION ERROR IN EYE

Rays from the Oculometer source (at virtual infinity) will be brought to a focus at a distance δx in front of the retina where

$$\delta x = f - x = f - fR/(R + f) = f^2/(R + f) \sim f^2/R$$

The diameter (δy) of the corresponding blur circle is given by

$$\frac{\delta y}{\delta x} = d/f$$

$$\therefore \quad \delta y = \delta x \, d/f = \frac{f^2}{R}\frac{d}{f} = \frac{fd}{R}$$

The angular size ($\delta\theta$) of the blur circle is given by

$$\delta\theta = \delta y/f = d/R$$

The value of $\delta\theta$ defines the degree of focus of the returned radiation from the eye as it is imaged onto the aperture A2 (in Figure 17). Obviously if the collection aperture diameter is made smaller than this blur, there will be a loss of efficiency in the bright pupil technique, because the aperture will not be able to collect all the returned radiation from the eye. For this reason it is useful to define

$$F_\beta = 1/\delta\theta$$

The efficiency of the bright pupil system, in relation to eye focus, depends upon the relative magnitudes of F, F_β.

For equal aperture and blur diameters $F = F_\beta$.

Accommodation is normally measured in diopters (D) (The power in diopters of the eye lens is defined to be the reciprocal of the anterior focal length in meters. The power of the normal eye is 60 diopters). The power change δD due to a focal length change δf is given by:

$$\frac{\delta D}{D} = - \delta f/f$$

Therefore, the power change due to accommodation from infinity to a point R from the eye is given by

$$(\delta D)_R = \frac{Df}{R}$$

Now $1/D = \frac{3}{4}$ f (when f is in meters)

$$(\delta D)_R = \frac{1.33}{R} \quad \text{when R is in meters}$$

As a worst case R can be taken as 6 in. Then

$$(\delta D)_R = \frac{1.33}{1/6} \approx 8 \text{ diopters.}$$

The distribution of ametrophia (refractive error in the eye) over the population is given in Ref 8. Less than 0.1% have a refractive error greater than 8 diopters. Thus an accommodation (or focusing) error of 8 diopters can be considered as a representative worst case condition.

For this worst case

$$F_\beta = 1/\delta\theta = R/d = \frac{150}{d}$$

where d is in millimeters.

As stated previously, the intensity of the pupil signal is a function of the state of accommodation and the Oculometer F number. It is convenient to derive this relationship in terms of normalized parameters:

F/number: $x = F/50$ (i.e., the normalized F/number is unity at F/50)

Accommodation $\beta = F_\beta/50$

Let the effective (bright) pupil signal (at F/50) due solely to the, sharp, central portion of the retinal image (i.e., excluding the diffuse background mentioned earlier), at $F_\beta = \infty$, be A units on some measuring scale (e.g. video level in volts, with a given illumination intensity and given image dissector).

Under the same conditions, let the diffuse background portion of the retinal image contribute a portion K to the effective (bright) pupil signal factor. Then the general pupil signal is given by:

$$P = \frac{A}{x^2 \, (1 + x^2/\beta^2)} + \frac{K}{x^4}$$

Let B be the intensity of the iris at F/50 on the same measurement scale used (above) for the pupil signal. Then the general iris signal is given by

$$I = B/x^4$$

These two expressions have been "manufactured" to agree with the following facts:

1) The iris signal is inversely proportional to F^4
2) The pupil signal, over to the large diffuse region of the retinal image, varies as F^{-4}
3) the pupil signal, due to the small sharply focused portion of the retinal image (with $F_\beta = \infty$) varies as F^{-2}
4) the pupil signal, in item (3) above, varies as F^{-4} when $F_\beta << F$.

It is possible to introduce the variable d into the equation for P above:

$$\beta = F_{\beta}/50 = \frac{150}{50d} = 3/d$$

or, in general, $\beta = \eta/d$ where the expected worst case is $\eta = 3$

Also $A = A_3 d^2/9$

Where A_3 is the value of A at d = 3mm.

$$\therefore \qquad P = \frac{A_3 d^2/9}{x^2\left(1 + \frac{d^2 x^2}{\eta^2}\right)} + \frac{K_3 d^2/9}{x^4}$$

This equation shows that the value of x for which accommodation errors becomes significant is

$$(x)_d = \eta/d \quad \text{ie } (x)_d = 1.5 \text{ for } d = 2\text{mm. } (\eta = 3)$$
$$= 0.6 \text{ for } d = 5\text{mm. } (\eta = 3)$$

An important operational parameter is the pupil tracking signal/noise ratio. This is proportional to:

$$\frac{\text{PUPIL SIGNAL} - \text{IRIS SIGNAL}}{\sqrt{\text{PUPIL SIGNAL} + \text{IRIS SIGNAL}}}$$

i.e.,

$$\left(\frac{S}{N}\right) \propto \frac{\dfrac{A}{x^2\,(1 + x^2/\beta^2)} + \dfrac{K}{x4} - \dfrac{B}{x4}}{\sqrt{\dfrac{A}{x^2\,(1 + x^2/\beta^2)} + \dfrac{K}{x4} + \dfrac{B}{x4}}}$$

$$= \frac{(A/B)\left\{\dfrac{x^2}{1 + x^2/\beta^2}\right\} + \left(\dfrac{K}{B}\right) - 1}{x^2\sqrt{\left[\dfrac{A}{B}\left\{\dfrac{x^2}{1+x^2\beta^2}\right\} + \left(\dfrac{K}{B}\right) 1\right]}}$$

This function is plotted in Figures 20 and 21 for various values of the parameters.

Introducing the pupil diameter d,

$$\left(\frac{S}{N}\right) = \frac{\left(\dfrac{A_3}{9B}\right)\left[\dfrac{d^2\,x^2}{\left(1 + \dfrac{d^2\,x^2}{\eta^2}\right)}\right] + \dfrac{K_3\,d^2}{9B} - 1}{x^2\sqrt{\left[\left(\dfrac{A_3}{9B}\right)\left[\dfrac{d^2\,x^2}{\left(1 + \dfrac{d^2\,x^2}{\eta^2}\right)}\right] + \dfrac{K_3\,d^2}{9B} + 1\right]}}$$

For simplicity consider the case when $K_3 = 0$. Pupil iris contrast is zero for a value of d given by:

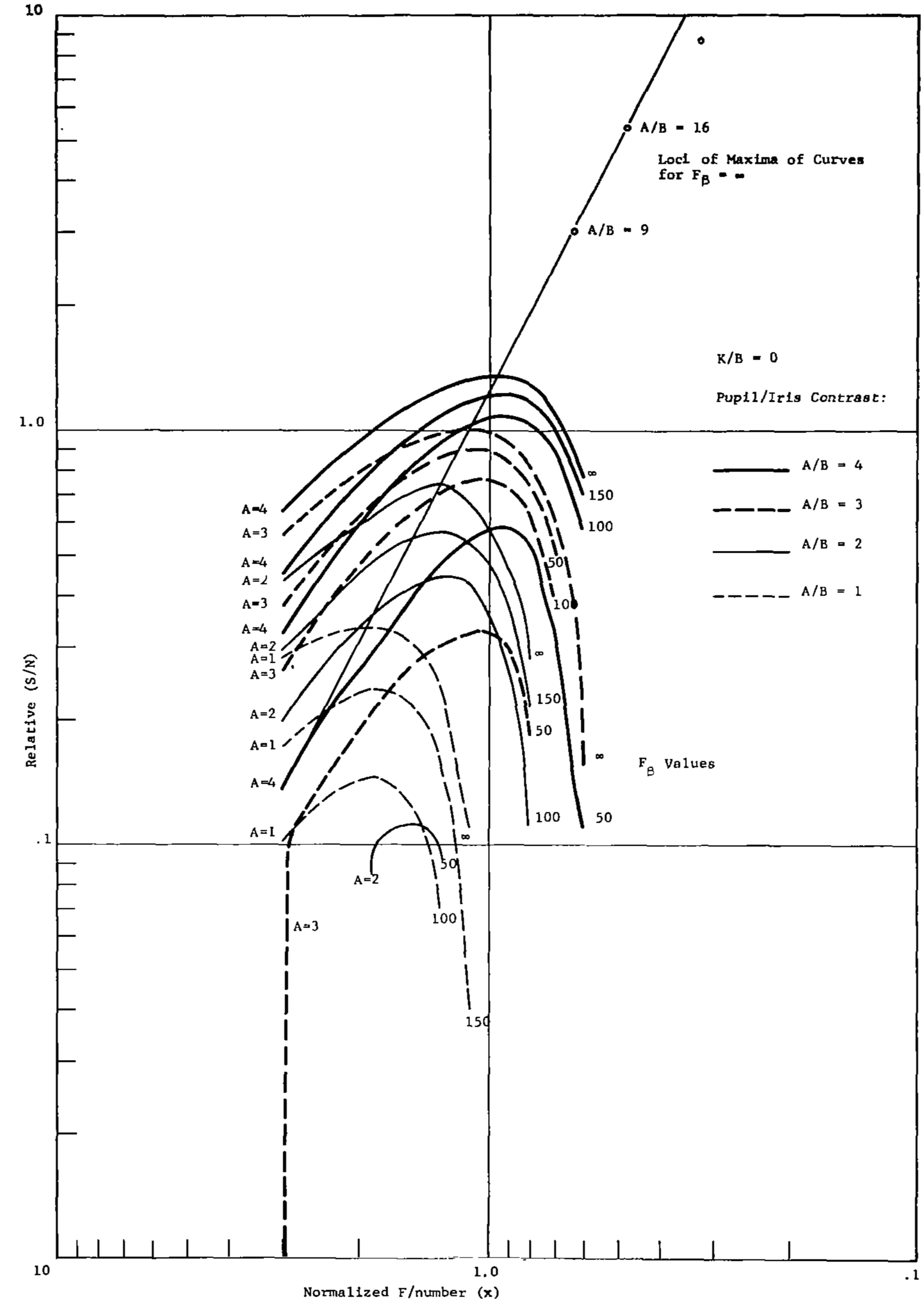


Figure 20 RELATIVE PUPIL TRACKING SIGNAL/NOISE RATIO

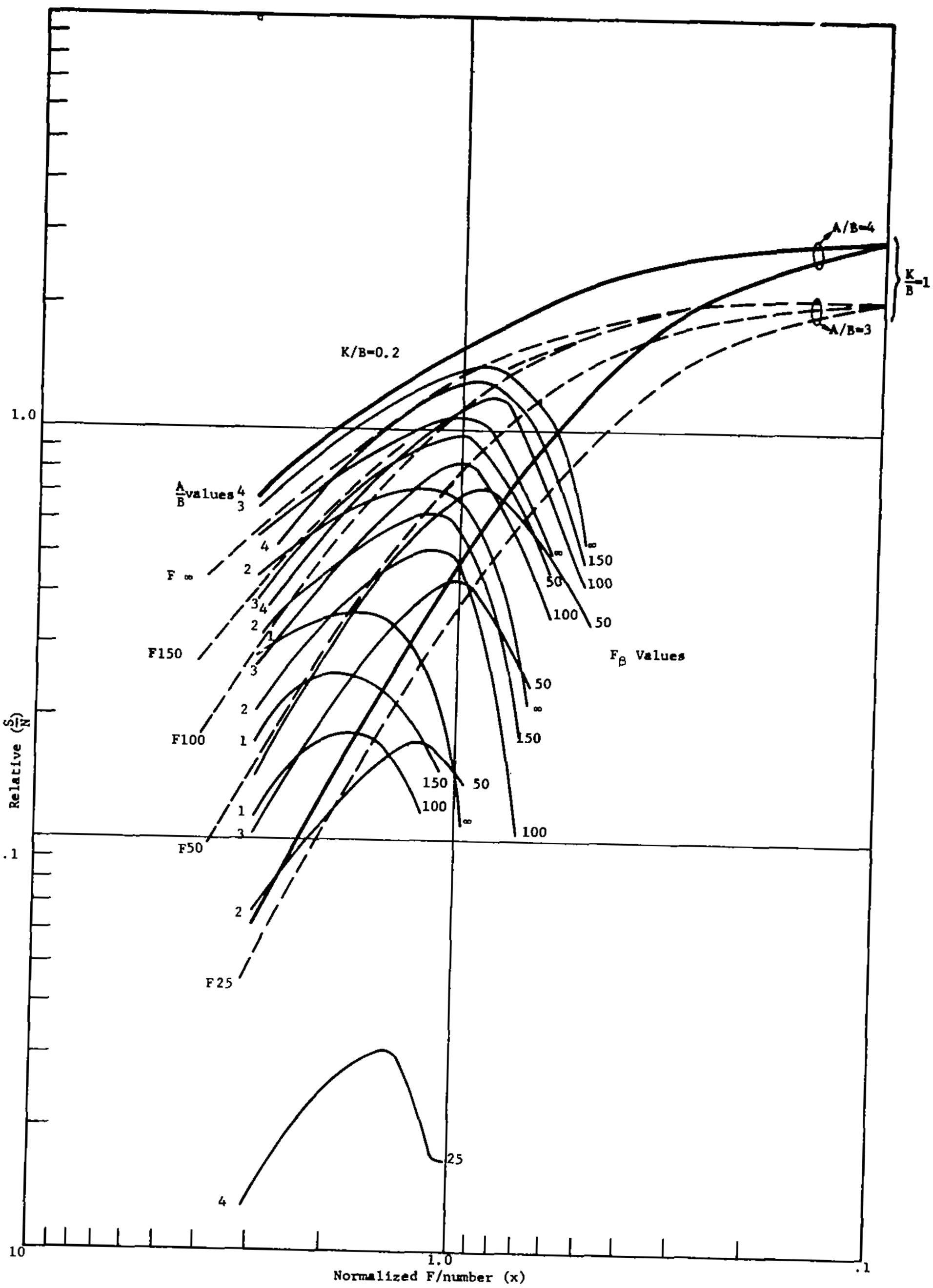


Figure 21 RELATIVE TRACKING SIGNAL NOISE RATIO

$$\frac{d^2 x^2}{1 + \frac{d^2 x^2}{\eta^2}} = \frac{9B}{A_3}$$

i.e.,

$$d^2 = \frac{1}{x^2} \left\{ \frac{A_3}{9B} - \frac{1}{\eta^2} \right\}^{-1}$$

Thus for effective tracking, with a minimum pupil diameter d_{min}, it is necessary that:

$$x > \frac{1}{d_{min}} \left\{ \frac{A_3}{9B} - \frac{1}{\eta^2} \right\}^{-\frac{1}{2}}$$

For d_{min} = 2mm and,

$$\left.\begin{array}{l} A_3 = .9 \\ B = .3 \end{array}\right\} \text{(worst case taken from Figure 18)}$$

η = 3 (worst case, as calculated above, for 8 diopters error)

Then,

$$x > \frac{1}{2} \left\{ \frac{.9}{9 \; (.3)} - \frac{1}{9} \right\}^{-\frac{1}{2}}$$

$$\text{i.e.,}\; x > \frac{1}{2} \left\{ \frac{1}{3} - \frac{1}{9} \right\}^{-\frac{1}{2}} \approx \frac{1}{2} \left\{ \frac{1}{4} \right\}^{-\frac{1}{2}}$$

i.e., $x > 1$

The value of η, below which tracking is impossible, is η', where

$$\eta' = 3\sqrt{\frac{B}{A_3}} = 3\sqrt{\frac{.3}{.9}} = \sqrt{3}$$

(This corresponds to an accommodation error of greater than 14 diopters)

Before summarizing the results of this section it should be noted that

a) there is some uncertainty in the absolute accuracy of the pupil reflectivity values shown in Figure 18 because the optical system used to generate the bright pupil effect was not maximally efficient. Thus the actual contrast may be higher (by as much as a factor of 2) than values shown in Figure 18.

b) The theoretical curves of Figures 20 and 21 are based upon a hypothetical model of the physical phenomenon. This model may not give an exact representation of all the physical factors involved.

It is concluded that

1) the F/number of the Oculometer system must be greater than a certain minimum value. This minimum value is inversely proportional to the minimum pupil diameter for which tracking is

to be effected. The analysis given here suggests that this minimum value (for a 2mm pupil) is about F/50 and that the optimum F number may be a about F/75. In particular it should be noted in the curves shown in Figures 20 and 21, the signal to noise ratio drops abruptly to zero near to the minimum value shown for each curve. For large values of x, the (S/N) simply falls off (eventually) as $1/x^2$. Thus it might be considered safer to operate to the left of the maximum of the curves shown in Figures 20 and 21.

2) Pupil tracking is impossible when very large accommodation errors exist. The 8 diopters maximum accommodation change of a normal eye does not appear to pose any problems. However, tracking is, according to the analysis given, impossible with accommodation errors greater than 14 diopters.

The Optical Signal

It is shown in reference 2 that the photocathode illumination (E_{pc}) due to the pupil is given by

$$E_{pc} = (k_R \tau^2) \left(\frac{d}{a}\right)^2 \left(\frac{1}{m^2}\right) \left(\frac{1}{F^2}\right) \left(\frac{\pi B_s}{16}\right) t_I \; t_c$$

where

k_R = the effective reflectance of the retina

τ = the transmission of the ocular media

d = pupil diameter (mm)

a = the focal length of the eye (mm)

F = Oculometer F/number (≈50)

t_I = transmission factor of the illumination optics

t_c = transmission factor of the collection optics

B_s = radiance of illumination source

m = optical magnification (photocathode image ÷ eye image)

Note that $(B_s t_I)$ is the apparent source radiance

Let N be the number of photoelectrons/s/cm^2 (area dimension referred to the eye) generated by the pupil image on the photocathode.

Then

$$N = E_{pc}\ K\ Q\ m^2 \text{ photoelectrons/s/cm}^2$$

where

K = a constant relating photons/s and watts ($K \approx 4.6 \times 10^{18}$ at 0.9μ)

Q = quantum efficiency of the photocathode ($\approx 3 \times 10^{-3}$ for S1 at $.8\mu - .9\mu$)

From Figure 18 it can be seen that the minimum value of pupil reflectivity (at 2mm pupil diameter) is 0.62 (and that the maximum iris reflectivity is 0.3). The reflection factor of the pupil, according to simple theory, is given by $R = (K_r\ \tau^2)\ (\frac{d}{a})^2\ F^2$.

$$\left[(K_R\ \tau^2)\ (\frac{d}{a})^2\right] \min = \frac{1}{F^2}\ 0.62$$

According to the nominal safety criteria established for the laboratory Oculometer:

$$(B_s\ t_I) \max = 1.5 \text{ watts/cm}^2\text{/steradians}$$

(However, it is to be noted that consideration may be given to controlling $(B_s\ t_I)$, according to the actual diameter of the pupil. In this event a considerable improvement in signal level, over the baseline signal level to be computed here, could be realized)

$$N = \left(4.6\right) 10^{18}\left(3\right) 10^{-3}\left(.62\right)\left(50\right)^{-4}\left(1.5\right)\left(\frac{\pi}{16}\right)\left(0.4\right)$$

(a value of 0.4 has been assumed for t_c and 50 for F)

$$= 1.61 \times 10^{8} \text{ electrons/s /cm}^{2} \text{ (at the eye)}$$

The photocathode illumination due to the corneal reflection (E_{cr}) is given (in Ref 2) by

$$E_{CR} = E_{pc} \frac{4\rho}{k_r \tau^2 \, (d/a)^2}$$

where ρ is the reflection factor of the cornea (about 2.5×10^{-2})

$$\therefore \quad N_{CR} = N_{pc} \left(\frac{10^{-1}}{.62}\right)\left(2500\right), \text{ (For F = 50)}$$

i.e. $N_{CR} \approx 400$ N

$$= 6.44 \times 10^{10} \text{ electrons/s/cm}^{2} \text{ (at the eye)}$$

The relative pupil and corneal signals are shown in Figure 22 for various pupil diameters, together with the relative intensity of possible interfering signals.

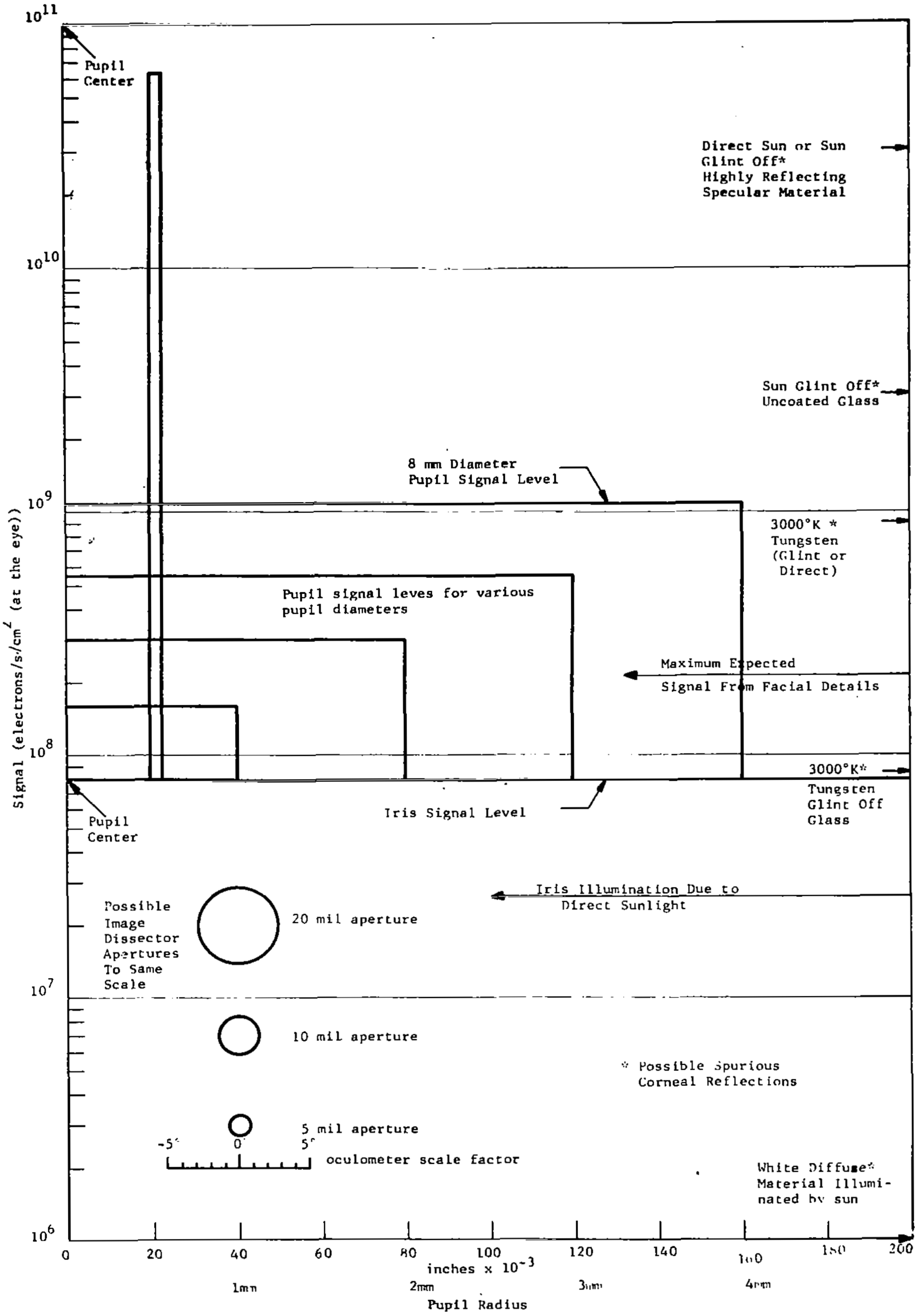


Figure 22 ELECTRO-OPTICAL SIGNAL LEVELS (BASED UPON $F=50$ $B_s t_I = 1.5 W/cm^2/sr$ XENON ILLUMINATION

Assuming that a one millisecond circular scan is used, (as in the mental alertness Oculometer) it is possible to calculate the electron flux per element of the circular scan for various scanning aperture diameters. The results are shown in Figure 23.

The Effect of Sunlight and Other Ambient Illumination

Ambient illumination can effect Oculometer operation in two ways:

1) Pupil/iris contrast will be degraded due to ambient illumination of the iris (a function of the ambient level at the eye in watts/cm^2 at 0.825μ)

2) Corneal reflections of ambient sources may interfere with pupil and corneal tracking (a function of the angular size, and the radiance in watts/cm^2/steradian at 0.825μ, of the ambient sources.)

The primary method to be used to overcome ambient effects is to ensure that:

1. The illumination at the eye due to the Oculometer is greater that that due to the ambient.

2. The radiance of the Oculometer source is greater that that of any ambient source.

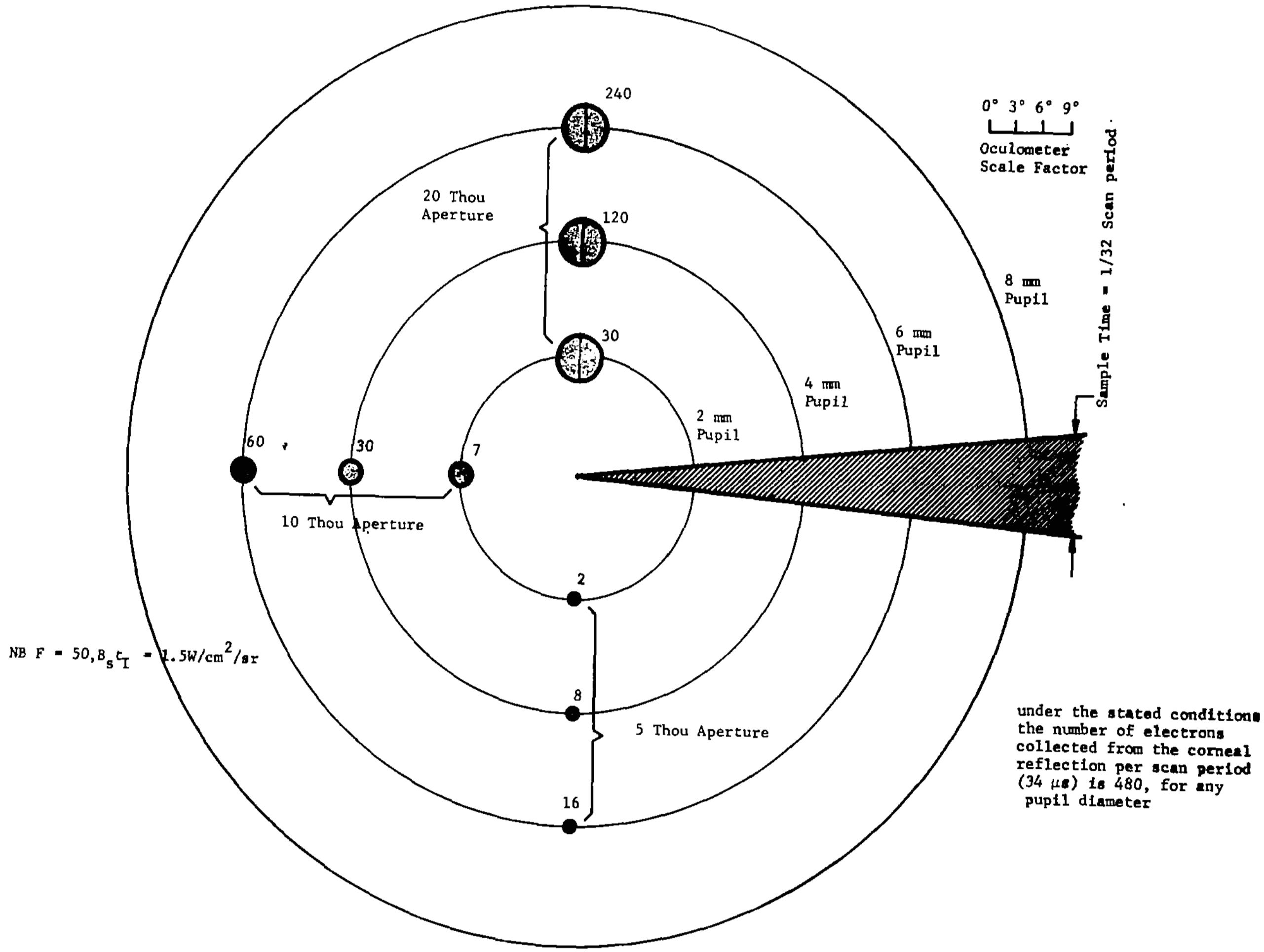


Figure 23 NUMBER OF ELECTRONS COLLECTED PER SCAN PERIOD (34 μs) BY THE APERTURE FROM THE PUPIL IMAGE FOR VARIOUS PUPIL AND APERTURE SIZES

The Oculometer source will subtend about 1 degree at the eye. The sun subtends just less then 1/2 degree. Thus, allowing for the optical loss factor introduced by the Oculometer illumination optics, the illumination at the eye due to sunlight will be about equal to the eye illumination of the Oculometer for equal sun and Oculometer source radiances.

The spectral radiance functions for the sun and typical xenon short arc lamps are plotted as functions of wavelength in Figure 24. It is evident that if the operating band of the Oculometer is confined to about 0.825μ ±0.01μ then the Oculometer source will have a higher effective radiance than the sun.

As noted above, ambient illumination can interfere with the operation of the Oculometer in the following ways:

1) Ambient illumination of the iris will lower the effective pupil/iris contrast. An approximate minimum (worst case) effective reflectance factor of the pupil (with the bright pupil technique) is 1.0 (at F/50). The maximum iris reflectivity is about 0.3. The effect on pupil/iris contrast, and the pupil tracking signal to noise ratio, in this worst case of minimum pupil brightness is plotted in Figure 25. It can be seen that the ambient illumination should (for this

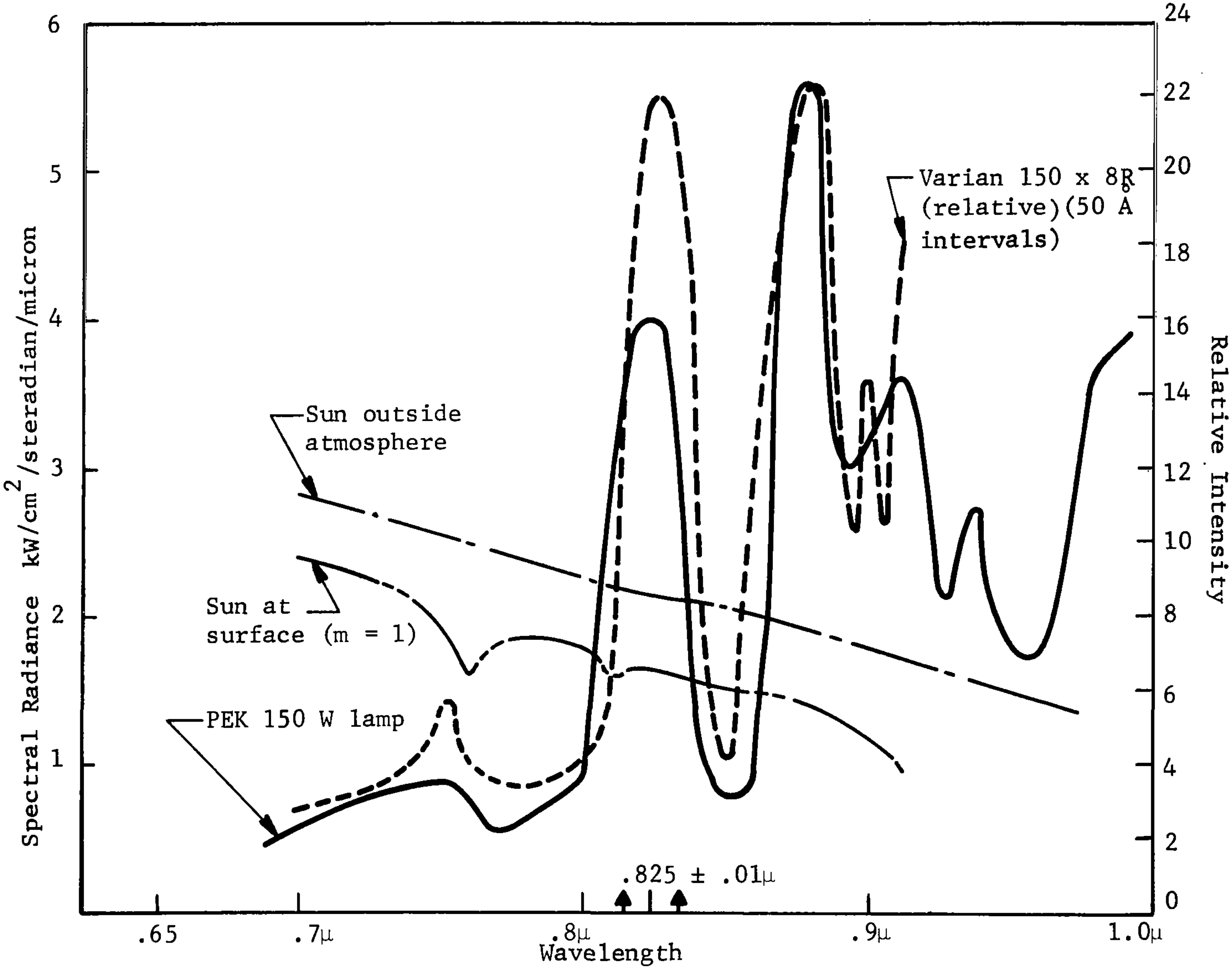


Figure 24 SPECTRAL CHARACTERISTICS OF XENON SHORT ARC LAMPS AND SUNLIGHT

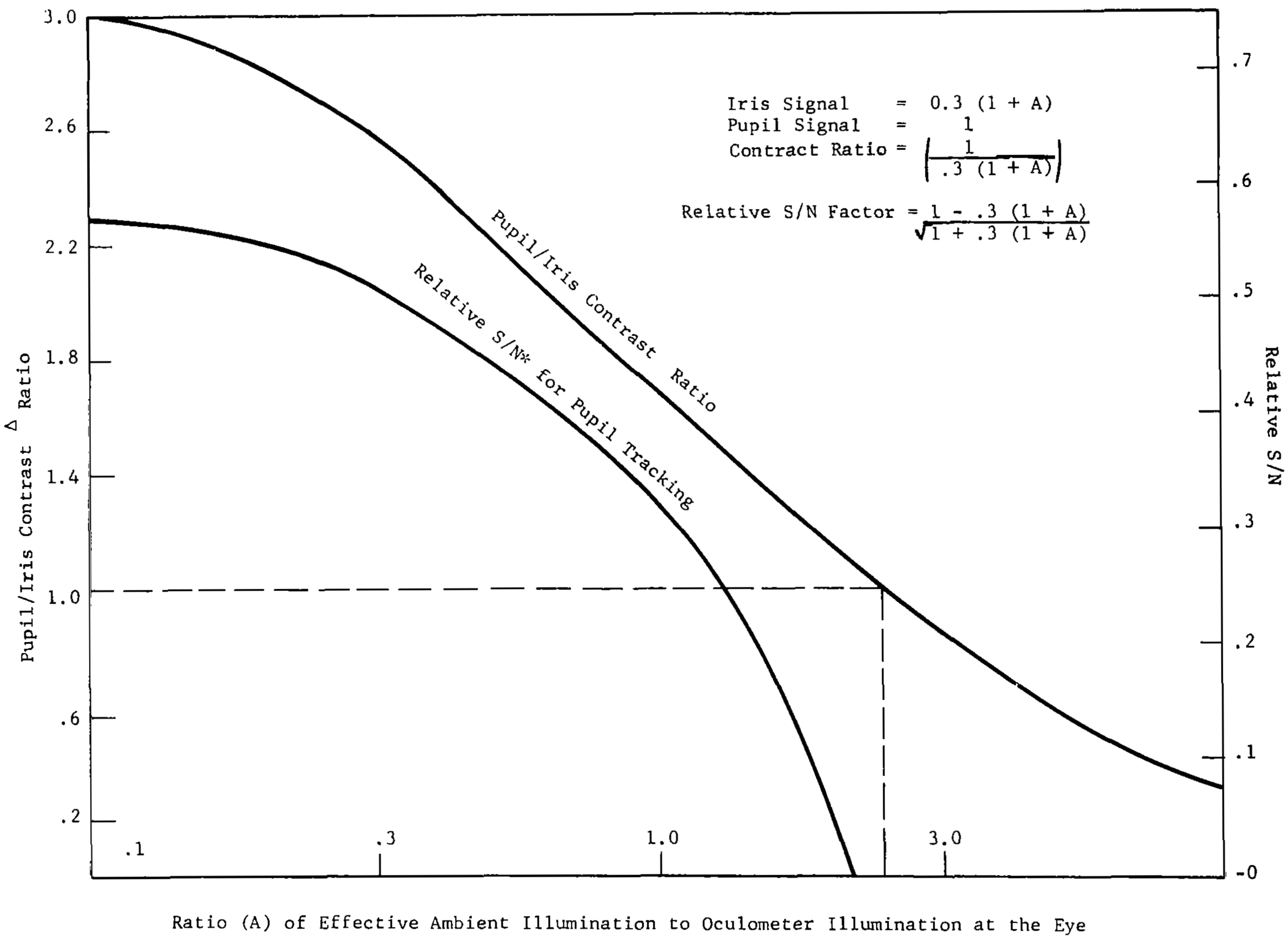


Figure 25 THE EFFECT OF AMBIENT ILLUMINATION ON PUPIL CONTRAST AND PUPIL S/N RATIO

worst case) be less than 30% of the Oculometer illumination in order to avoid any significant interference with the pupil tracking function.

2) A corneal reflection will be formed of any ambient source (or of reflections of any ambient source) that fall within about ±70 degrees of the foveal gaze vector. These reflections could possibly interfere with either

a) The corneal acquisition and tracking system or

b) The pupil acquisition and tracking system.

Corneal acquisition will be unreliable unless the effective intensity of the spurious corneal reflections are less than 30% of the corneal reflection of the Oculometer source. There is, in general, little likelihood of any direct interference to the corneal tracking system by false corneal reflection of the sun because the area immediately surrounding the Oculometer source aperture will obscure the direct rays from any potentially interfering source (such as the sun). Specular reflections from the Oculometer aperture and surrounding panel areas should be minimized - by suitable choice of materials using antireflection coatings etc. so that they will not interfere with corneal acquisition.

Spurious corneal reflections will not interfere with pupil acquisition because they exist within, or near to, the pupil area and thus can only help, not hinder, pupil acquisition..

The effect of spurious corneal reflections on corneal and pupil tracking represents a more difficult problem. Let ϕ be the ratio of the Oculometer source radiance to that of the interfering source. Let g be the angular size of the interfering source in radians.

Let δ be the diameter at the eye of the image dissector (ID) scanning aperture. Then the spurious corneal reflection will be 0.15g in. in diameter and of intensity ϕ relative to the system corneal reflection. The typical worst case situation is illustrated in Figure 26 in which the separation of the two reflections is equal to the radius of the scanning aperture $(\frac{\delta}{2})$.

The relative intensity of the two reflections is:

$$1 \times (.003)^2 : \phi \times (.15g)^2$$

The corneal tracking error is then $\approx$

$$\frac{\delta}{2} \phi \, (50g)^2 \text{ or } \delta\phi g^2 (1250) \text{ inches}$$

of if δ is expressed in 10^{-3} inches

tracking error = $4 \times 10^{2}\ \delta\phi g^{2}$ degrees

The pupil tracking error is calculated as follows for the worst case, shown in Figure 26B.

Pupil signal relative to corneal reflection signal = $\frac{\delta^{2}}{4000}$
(where δ is in 10^{-3} inches)

Intensity of interfering signal (relative to corneal reflection) = $\phi(50g)^{2}$

Duty cycle ratio of interference = $\frac{\delta}{250}$
(assuming δ is larger than the spurious corneal reflection)
Effective magnitude of interference signal = $\frac{\phi\ (50g)^{2}(\frac{\delta}{250})}{(\delta^{2}/4000)}$ x pupil signal

Therefore, tracking error $\approx$

$$\frac{\delta}{2}\ \frac{(50g)^{2}\ (\frac{\delta}{250})\ \phi}{(\delta^{2}/4000)}\quad 10^{-3}\ \text{inches}$$

$$= (2)(10^{4})(\phi g^{2})\quad 10^{-3}\ \text{inches}$$

$$= (7)(10^{3})\ \phi g^{2}\ \text{degrees}$$

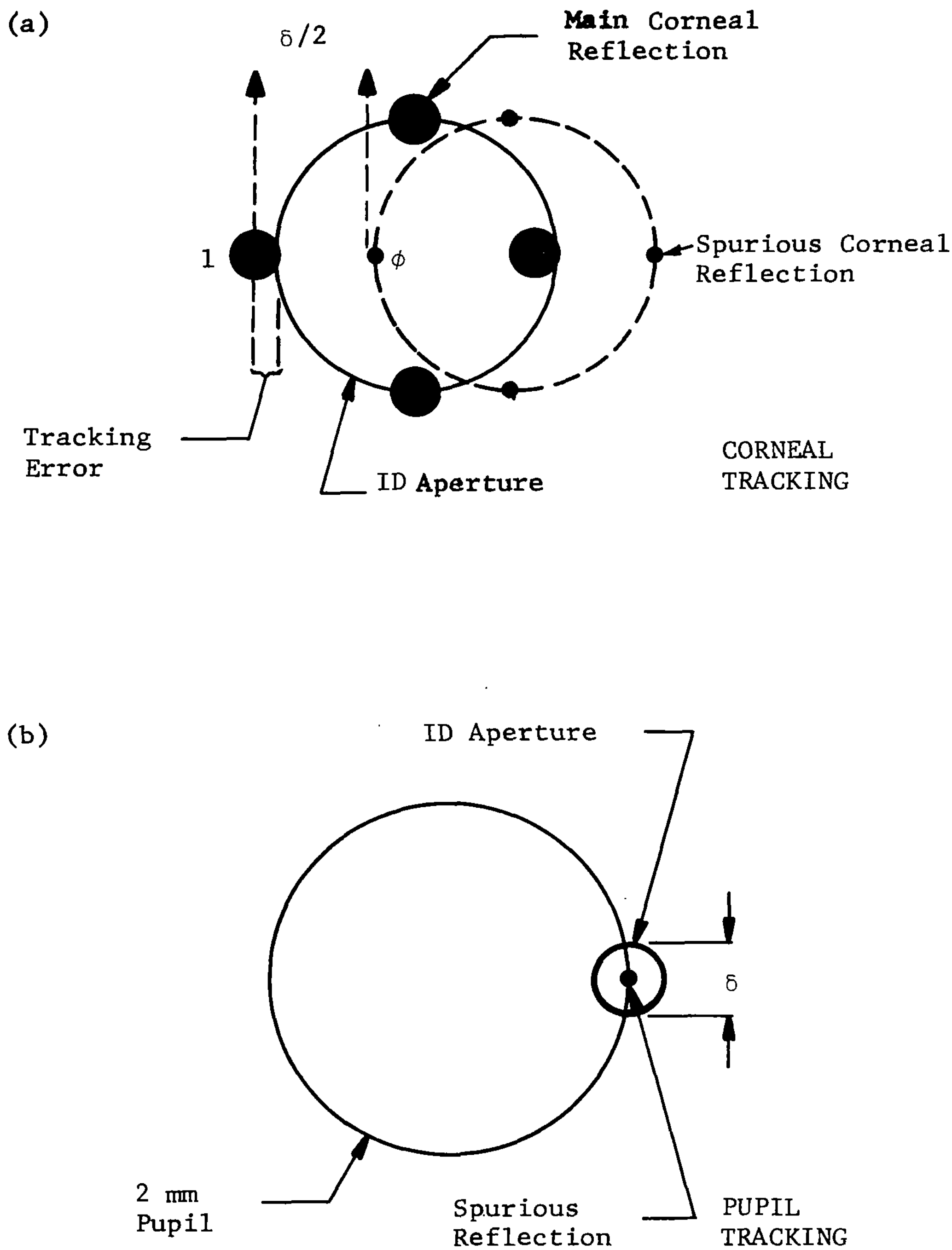


Figure 26 THE EFFECT OF SPURIOUS CORNEAL REFLECTIONS

This analysis has shown that the error in pupil tracking due to a spurious corneal reflection is independent of the ID aperture diameter δ, whereas the error in corneal tracking is directly proportional to δ. The pupil and corneal tracking errors due to a small spurious corneal reflection are equal when the ID aperture is about 0.02 in. diameter. Since this is probably the largest aperture that will ever be considered for use in any Oculometer, it follows that the total error effect of spurious corneal reflections is independent of ID aperture diameter. This error is plotted as a function of g and ϕ in Figure 27. Provided that the size of the spurious reflection source (e.g., the glint area on the instrument panel) is small (e.g., a few mm) the error due to spurious corneal reflections will be negligible.

Obviously the direct corneal reflection of the sun could occur on or near the pupil iris boundary and thereby severely interfere with pupil tracking (for the sun, $g \approx 0.01$ radians, $\phi \approx 1$ (assuming a xenon Oculometer illumination). To overcome the sun error in this case, the pupil tracking video should be set at the nominal tracking level wherever the instantaneous level exceeds a threshold value (See Figure 28).

In summary perhaps the worst effect of intense direct sunlight is a reduction in pupil/iris contrast leading to about a factor of 2 increase in the signal/noise ratio (Figure 25). In most cases the effect of corneal reflections (direct or indirect)

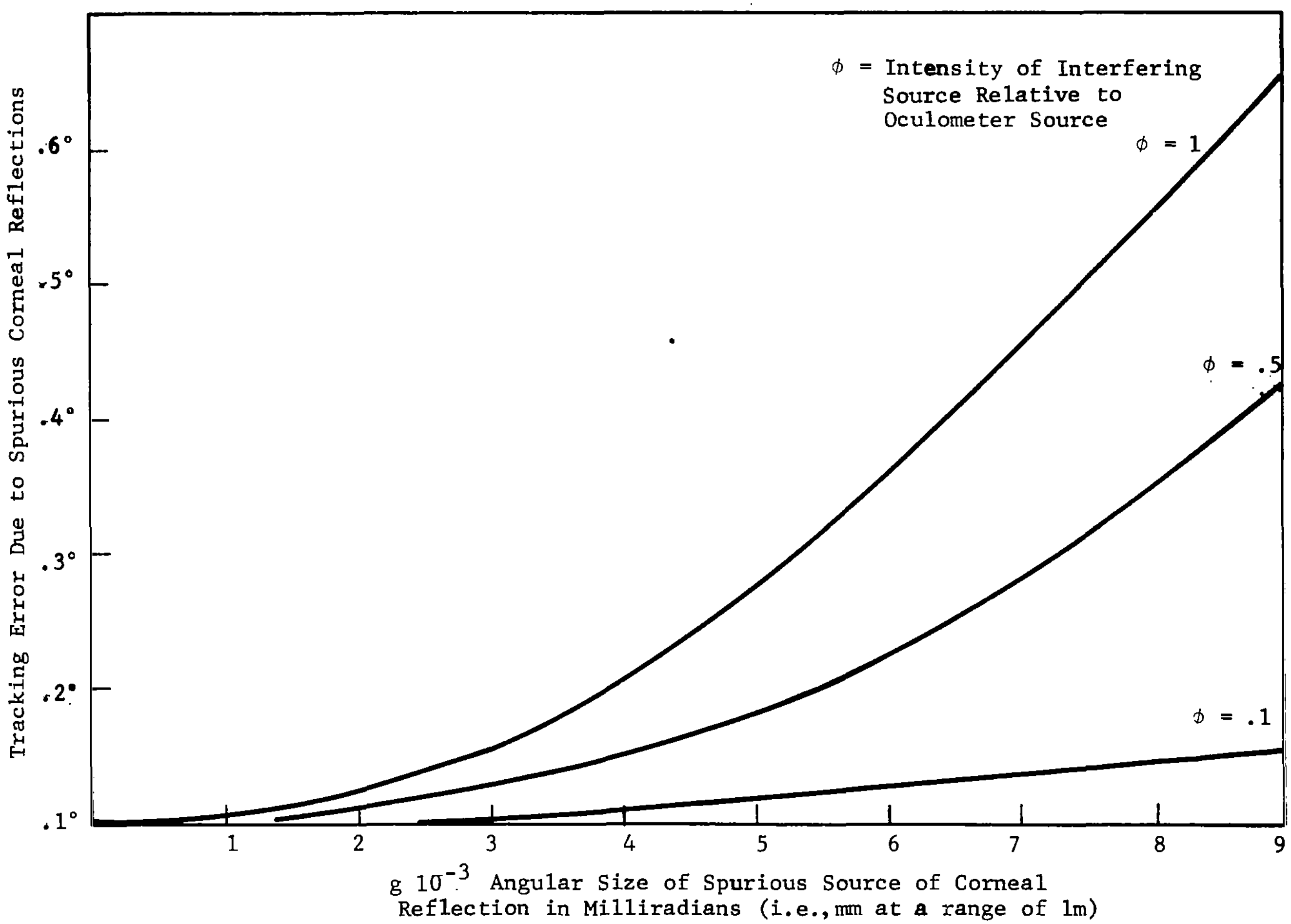


Figure 27 TRACKING ERROR DUE TO SPURIOUS REFLECTIONS

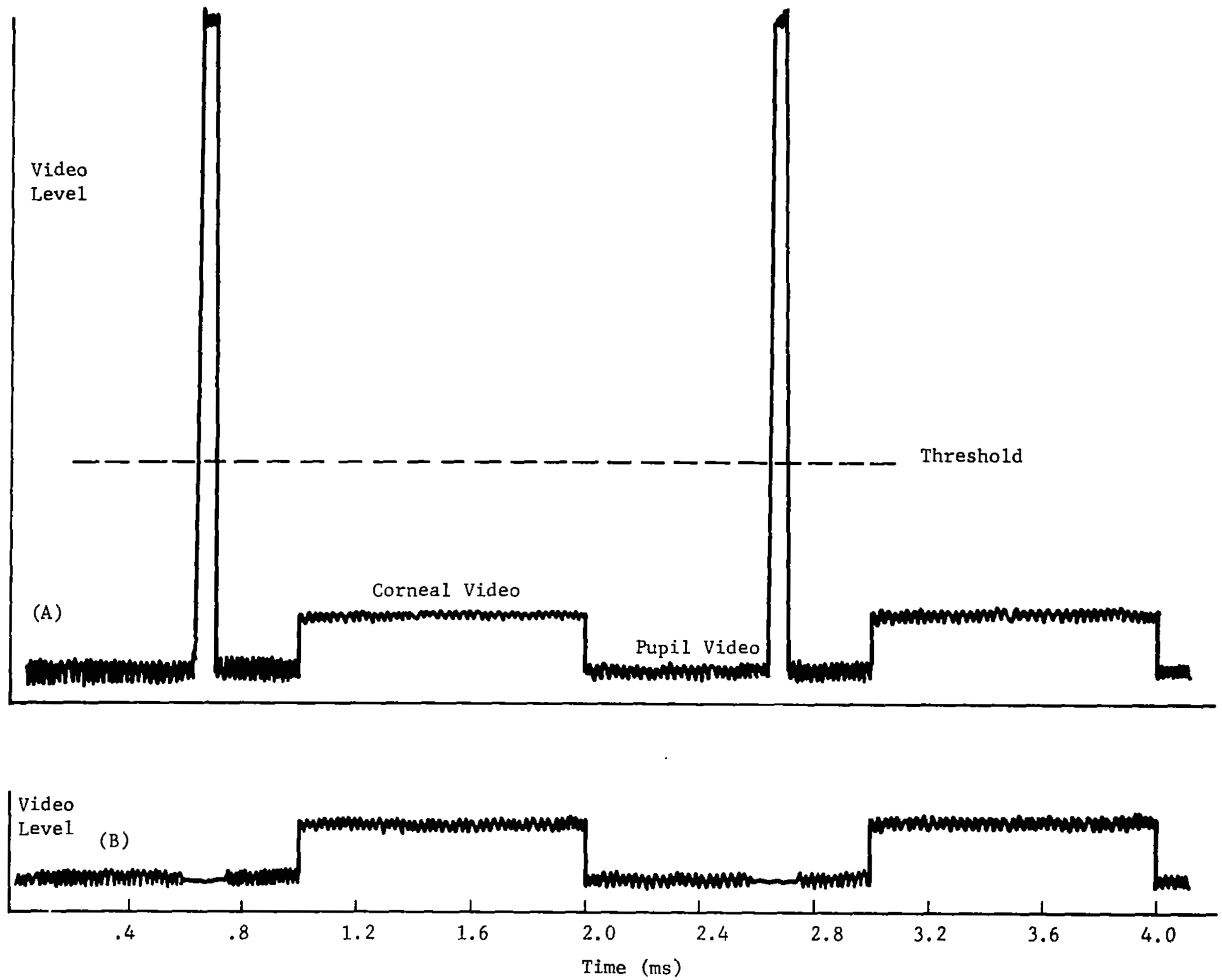


Figure 28 VIDEO SIGNAL WITH CORNEAL REFLECTION OF SUN ON PUPIL/IRIS BOUNDARY
A. UNCORRECTED VIDEO
B. SUN SIGNAL CLAMPED OUT

of the sun are not serious. That is, the errors involved are of the order of 0.1 degree, depending upon the effective size of the ambient source (usually a glint reflection) (Figure 27).

Under ambient conditions that are less severe than that of direct sunlight, the errors involved rapidly become negligible. This is evident from Figures 29 and 30 which show the spectral radiance of various ambient sources for various levels of ambient illumination. These figures show, in effect, that direct sunlight (assumed as a worst case condition in the analysis above) is a much more severe environment than is usually encountered.

In other words, by using a xenon short arc illumination source, the effects of ambient illumination are made negligible in all cases except direct sunlight. Even then the errors involved are relatively small.

Subjective Visibility of the Illumination Source and Signal/Noise Ratio

Although the spectral band of the illuminating radiation is in the near infrared, outside the nominal visual band, the source may still be visible because of its high radiance and the fact that the eye has some sensitivity out to 1μ.

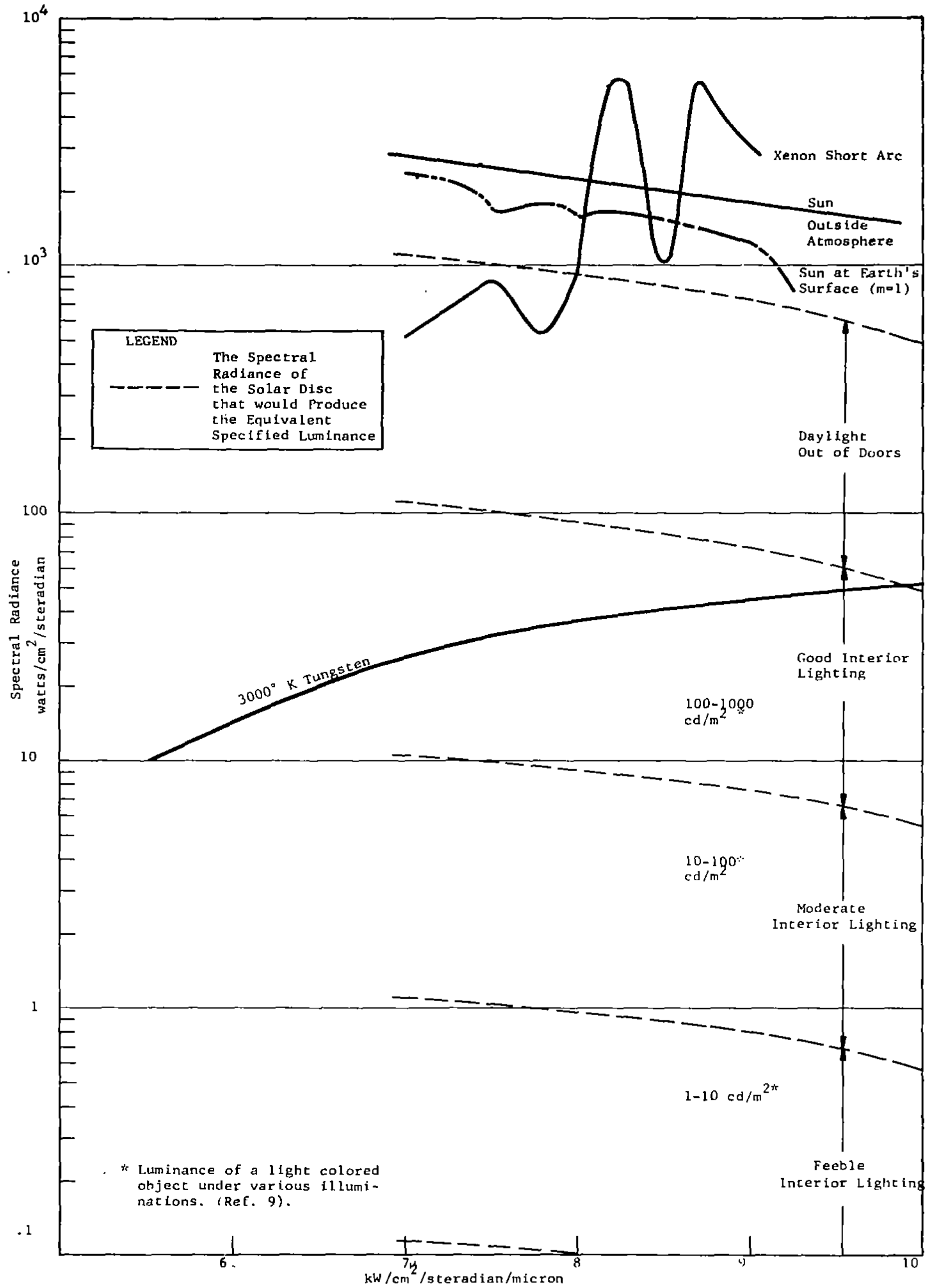


Figure 29 RELATIVE AMBIENT (SUN) SPECTRAL RADIANCES AS A FUNCTION OF LUMINANCE

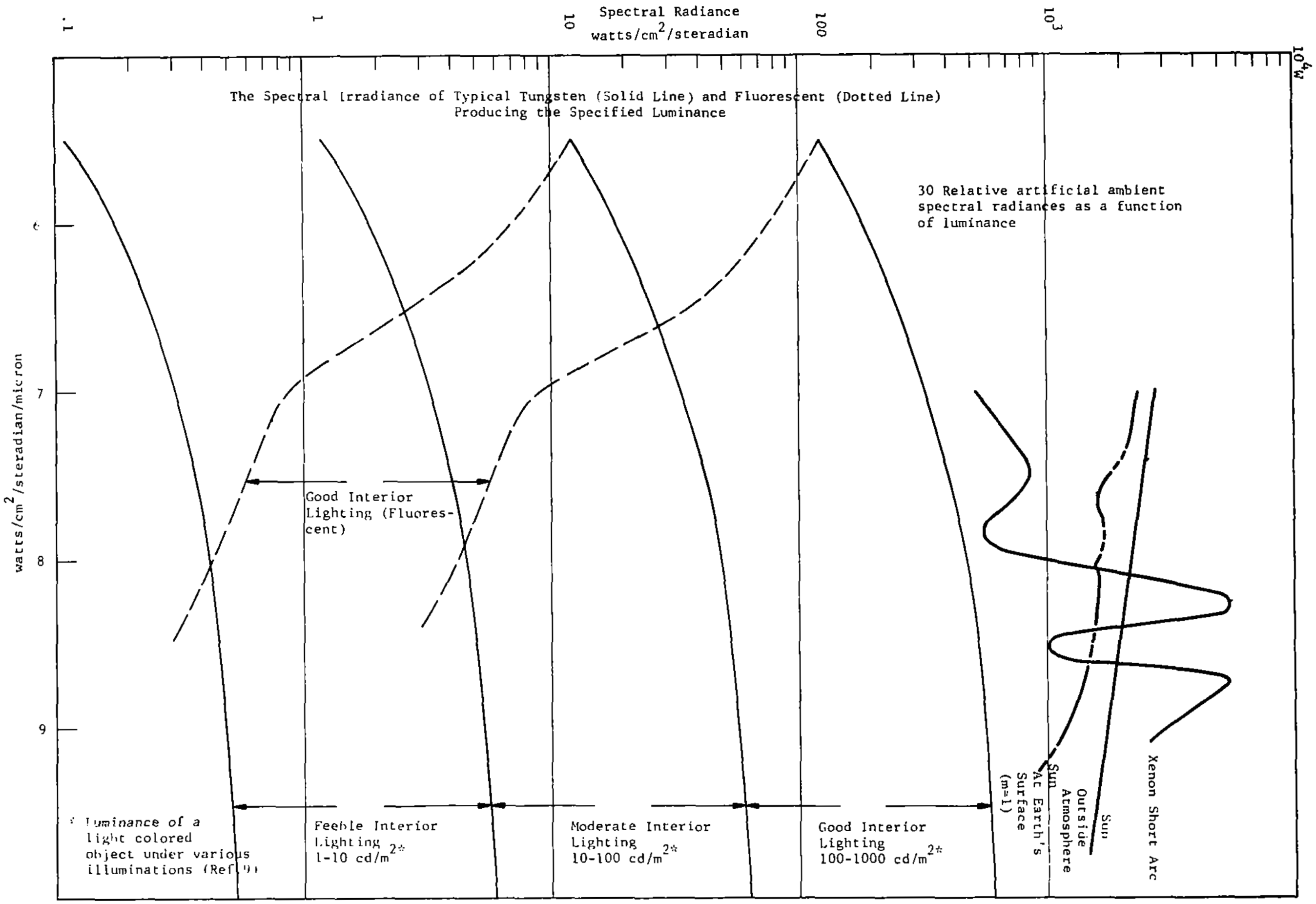


Figure 30 RELATIVE ARTIFICIAL AMBIENT SPECTRAL RADIANCES AS A FUNCTION OF LUMINANCE

The spectral response of the human eye is plotted in Figure 31 over the range 0.35μ to 1.0μ.

Consider a source radiance of 1.5 watts/cm^2/steradian. If the radiation were concentrated at 0.55μ its subjective luminance would be 10^7 candles/m^2 (600 lumens = 1 watt (approximately) at 0.55μ). The visual response curve shown in Figure 31 enables the actual luminance of the source to be computed as a function of wavelength (Figure 32).

In order to determine whether the source will actually be seen, it is necessary to refer to liminal threshold function of the human eye. This function can be defined as the value of log $\Delta L/L$, where L is the luminance of the background and ΔL is the luminance of a just distinguishable central region subtending 1 degree at the eye. This function is plotted in Figure 33. The derived value of log ΔL is also plotted in this figure.

Suppose the average scene luminance (L) (in the Oculometer environment) is 10^3 cd/m^2 (very good interior lighting). The just noticeable contrast ΔL is then 10 cd/m^2 (From Figure 33). Thus if the Oculometer source is to be only just noticeable at this value of scene luminance,it should be at a wavelength of 0.82μ (See Figure 32). If, on the other hand, the Oculometer source is to appear equally bright as the scene, then (from Figure 32)

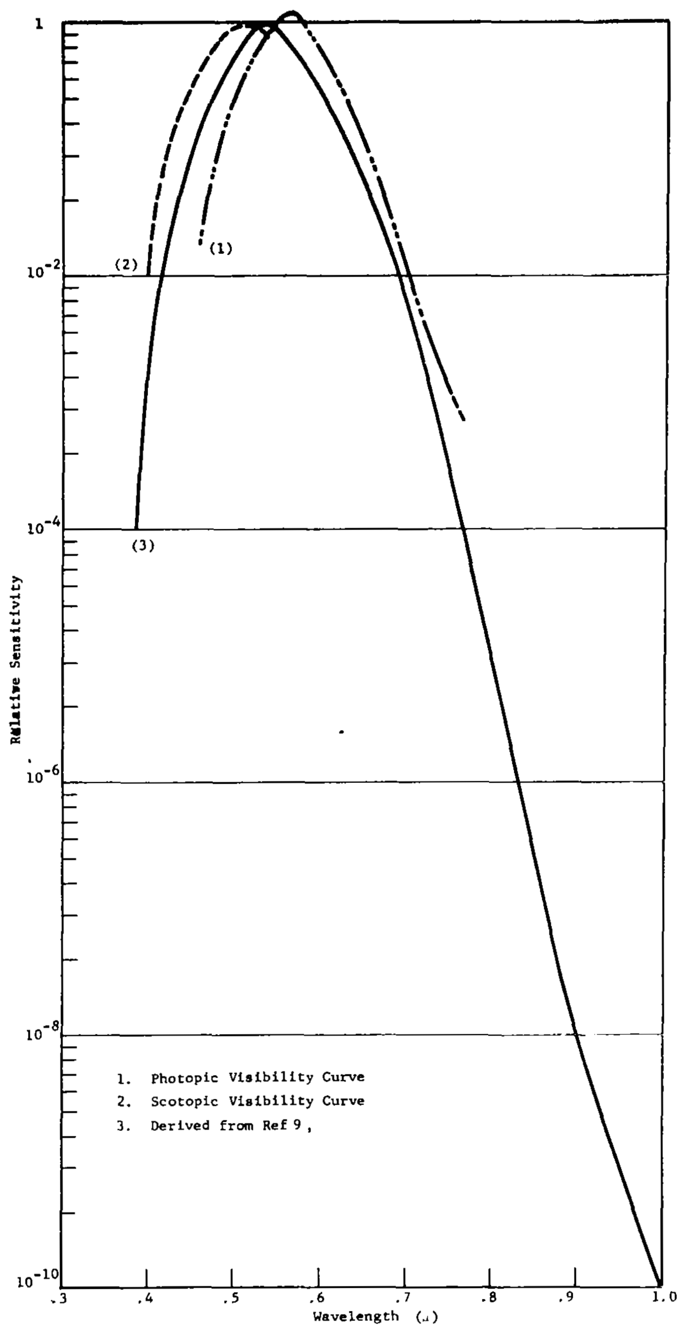


Figure 31 SPECTRAL RESPONSE OF THE HUMAN EYE

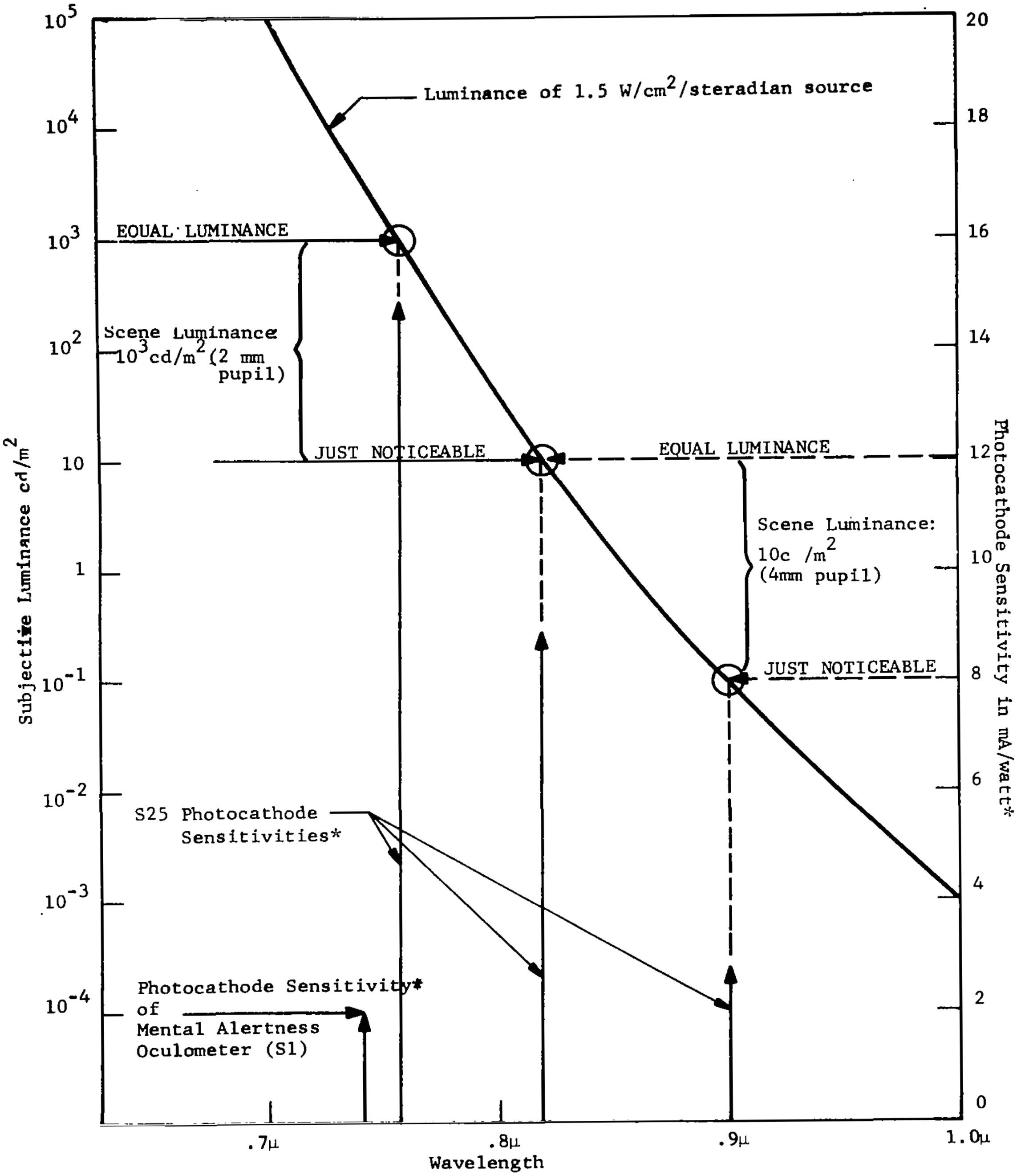


Figure 32 SUBJECTIVE LUMINANCE OF A 1.5W/cm^2/sr SOURCE AS A FUNCTION OF WAVELENGTH

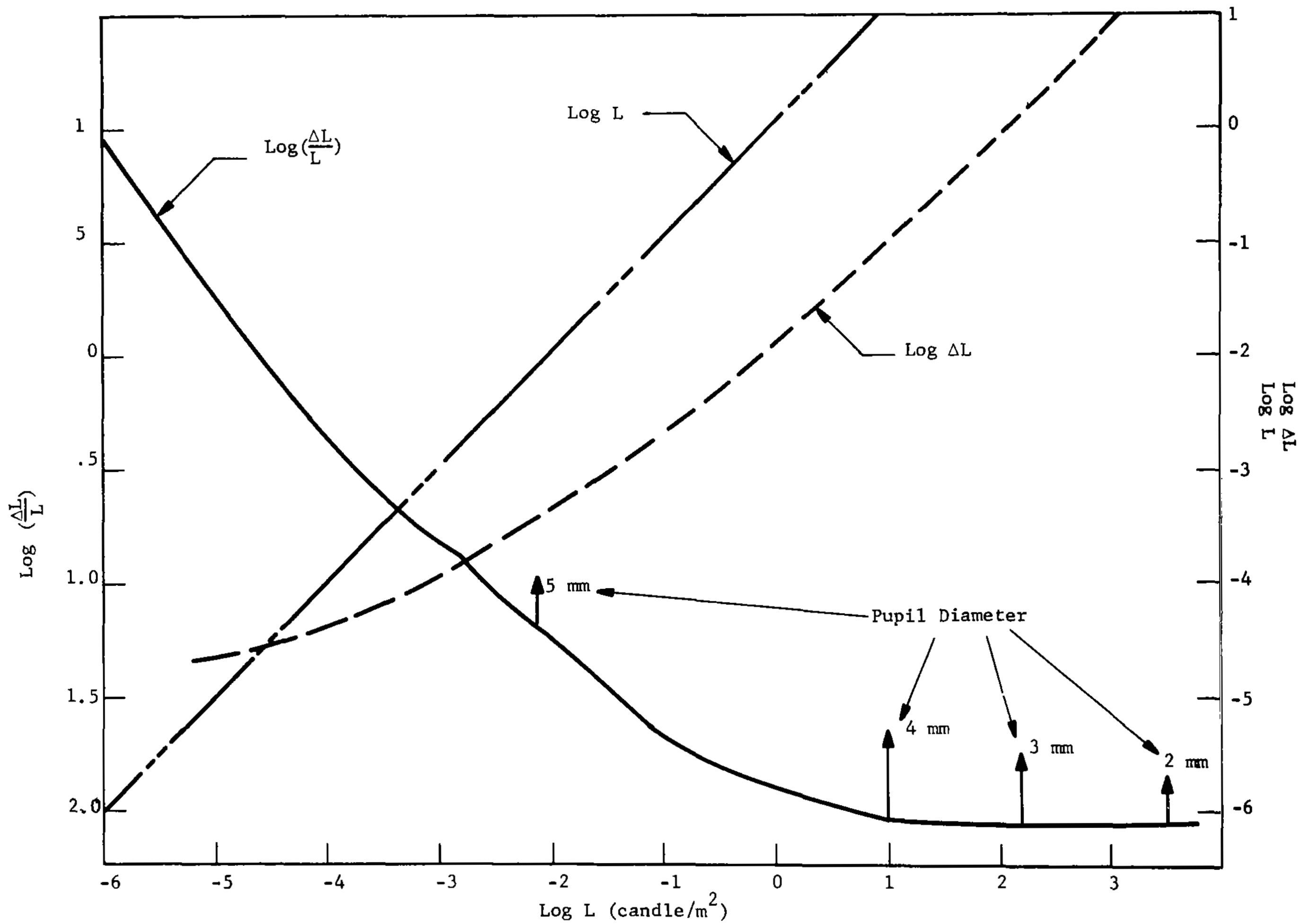


Figure 33 LIMINAL DISCRIMINATION CURVES

the wavelength should be 0.76μ. For a scene luminance of 10 cd/m^2 (feeble to moderate interior lighting) the wavelength of the Oculometer radiation, should be:

- for just noticeable visibility 0.9μ
- for equal luminance as the scene 0.82μ

However, if the source radiance is to be 10 times the value assumed in the discussion above (i.e., 15 instead of 1.5 watts (cm^2/steradian) the wavelength of the radiation must be increased by about 0.035μ to maintain the same visibility criterion.

The choice of operating wavelength effects the accuracy (noise level) of the Oculometer because the quantum efficiency of the image dissector photocathode varies with wavelength (Figure 34).

An apparent Oculometer luminance ten times the ambient background may also be considered. This would permit the operating band to be displaced to a lower wavelength and a correspondingly higher sensitivity obtained.

If, however, the system is to operate under extreme sun ambient conditions, then the operating wavelength must be either 0.825μ or else 0.88μ in order that the greatest possible sun discrimination can be obtained. (see location of xenon peaks in, for example, Figure 30). Table I shows the various possibilities and benefits obtained.

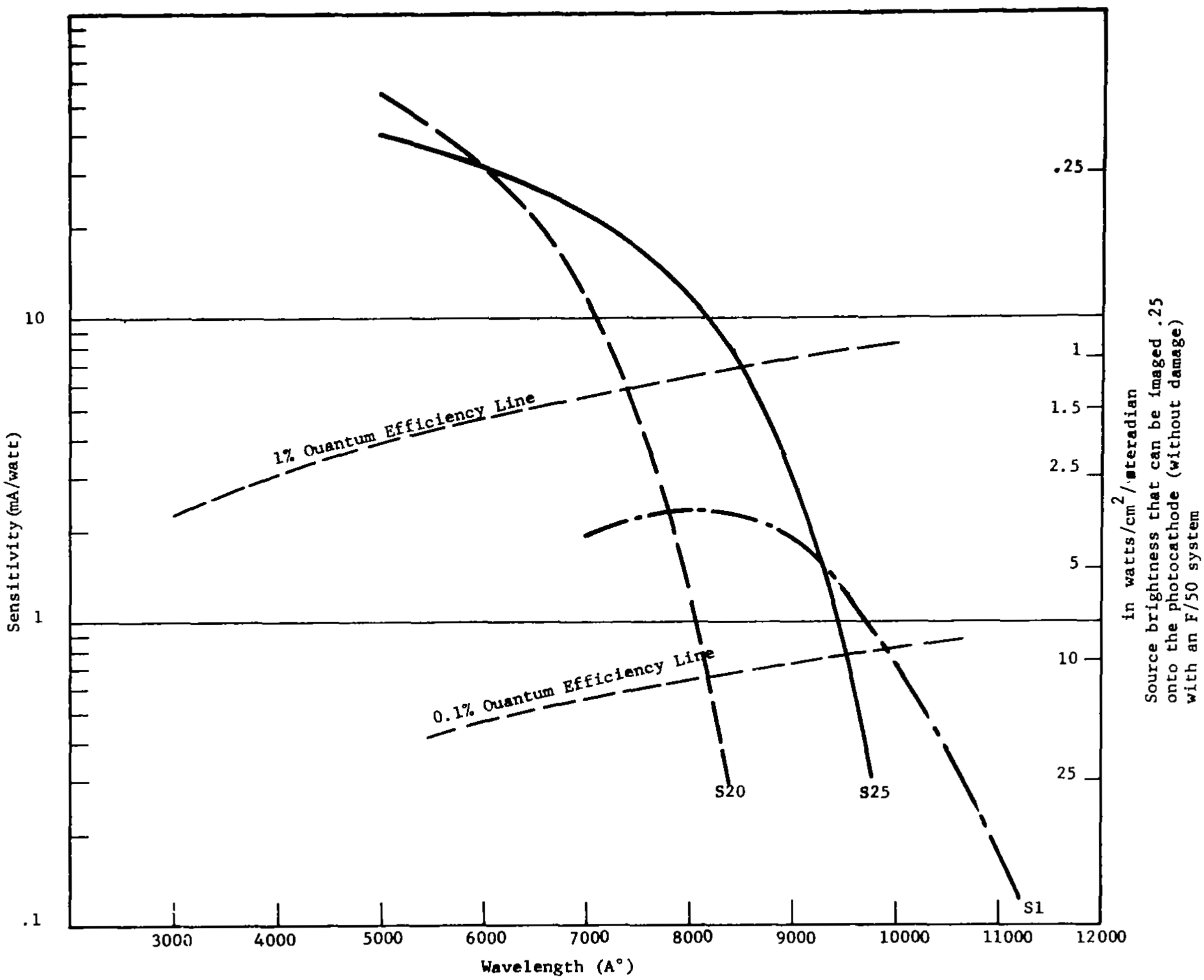


Figure 34 PHOTOCATHODE SENSITIVITY

Table I POSSIBILITIES AND BENEFITS

SCENE LUMINANCE	MAXIMUM SUN DISCRIMINATION	VISIBILITY CRITERION	WATTS/cm/STERADIAN SOURCE RADIANCE	λ MICRONS	PHOTOCATHODE SENSITITIVY ma/WATT S25	S1	S25 RELATIVE SENSITIVITY	SENSITIVITY RELATIVE TO MENTAL ALERTNESS OCULOMETER (Typical Worse Case rms Noise Level with 20 ms Smoothing)
10 cd/m^2	NO	Just Noticeable	1.5	.9	3	1.9	3	1.5 (.35°)
		Equal	1.5	.89	9.2	2.3	9.2	4.6 (.2°)
		10X Ambient	1.5	.79	12	2.3	12	6 (.18°)
		Just Noticeable	15.	.95	.8	1.2	8	4 (.21°)
		Equal	15.	.9	3	1.9	30	15 (.11°)
		10X Ambient	15.	.82	9.2	2.3	92	46 (.06°)
1000 cd/m^2	NO	Just Noticeable	1.5	.82	9.2	2.3	9.2	4.6 (.2°)
		Equal	1.5	.76	15	2.3	15	7.5 (.16°)
		10X Ambient	1.5	.73	17	2.2	17	8.5 (.14°)
		Just Noticeable	15.	.855	5.8	2.3	58	29 (.08°)
		Equal	15.	.79	12.	2.3	120	60 (.06°)
		10X Ambient	15.	.76	15.	2.3	150	75 (.05°)
10	YES	Equal	1.5	.825	9.2	2.3	9.2	4.6 (.2°)
		10X Ambient	15	.825	9.2	2.3	9.2	46 (.06°)
1000	YES	Just Noticeable	1.5	.825	9.2	2.3	9.2	4.6 (.2°)
		Visible But Not Equal	15.	.825	9.2	2.3	92.	46 (.06°)
10	YES	Visible But	1.5	.88	3.5	2	3.5	1.75(.32°)
		Not Equal	15.	.88	3.5	2	35	17.5 (.1°)
1000	YES	Invisible	1.5	.88	3.5	2	3.5	1.75(.32°)
		Visible But Not Equal	15	.88	3.5	2	35	17.5 (.1°)

Table I gives the product of S25 sensitivity (in mA/watt) and a factor which is 1 when the source radiance is 1.5 watts/cm^2/steradian and which is 10 when the radiance is 15 watts/cm^2/steradian. This product is a measure of the relative sensitivity of the corresponding Oculometer system. In the last column of the table this relative sensitivity figure is, in each case, degraded by 2 which was the corresponding relative sensitivity of the mental alertness Oculometer. Thus the final column gives a figure of relative improvement (in sensitivity) of each set of Oculometer parameters that are specified in the table over the mental alertness Oculometer.

Photocathode Damage

The average cathode current density for an S1 or S25 surface, must not be allowed to exceed 1μA/cm^2. At the peak sensitivity of the S1 surface (3mA/watt) the incident power must be held below 1/3 mW/cm^2.

Let B be the radiance of the only source that is imaged onto the photocathode by the Oculometer. Then, for no photocathode damage:

$$\frac{\pi B t_c}{4 F^2} < 0.33 \; 10^{-3} \; W/cm^2$$

Where t_c is the transmission factor of the collection optics and F is the Oculometer F/number. Assuming F = 50, t_c = .4 then

$$B < \frac{0.33\ 10^{-3}\ 4(2500)}{.4\pi}$$

i.e., $B < 2.5$ watts/cm^2/steradian

This limit is inversely proportional to the photocathode sensitivity. The actual limit for any cathode, at any wavelength, can be obtained from the right hand scale of Figure 34.

If the Oculometer source radiance is made greater than the limit as specified on Figure 34, then photocathode damage will result if a highly reflecting specular reflector occurs - e.g., a tie clip appearing in the eye space. Also direct sunlight or sun glint will cause photocathode damage (on a xenon system) if the specified limit is exceeded, because the sun's spectral radiance is approximately the same as the Oculometer spectral radiance. (However, a xenon Oculometer system having an effective source radiance of less than 2.5 watts/cm^2/steradian can safely be pointed directly at the sun).

If an image intensifier is used ahead of the image dissector the maximum optical signal must be limited so that

a. The photocathode of the intensifier is not damaged (same criterion as for image dissector without intensifier).

b. The intensified phosphor must not be damaged (limits the cathode current to about $0.08\mu A/cm^2$ (e.g., see RCA specification for tube type C33020E, minimum useful area/maximum photocathode current).

c. The S20 photocathode of the image dissector following the intensifier must not be damaged by the image on the (typically P20) phosphor screen. Allowing for the ten times lower damage threshold in the region of 0.6μ, and assuming a power gain for the tube of 10, the input current density must be limited to $0.01\mu A/cm^2$.

In other words, one of the penalties incurred in using the image intensifier is a reduction in the photocathode damage threshold by a factor approximately equal to the effective sensitivity gain of the tube. Specifically, an intensifier system could safely give a sensitivity gain of only about 30, with a source radiance of 1.5 watts/cm^2/steradian. Above this figure the corneal reflection in the eye image itself will damage the dissector photocathode. However, if the system were to be operated in this condition extreme care would have to be taken to avoid any specular reflections (e.g., of tie clips) of the Oculometer source from entering the collection optics.

In summary the photocathode damage problem appears to rule out the possibility of using an image intensifier/image dissestor combination.

If the system were designed to yield any useful increase in performance (sensitivity) it would be so susceptible to damage that it would be impractical to operate.

The radiance of the Oculometer source can be raised to 15watts/ cm^2/steradian (as discussed in the previous Section) without causing direct photocathode damage. However the system could not then be safely exposed to direct sunlight. Precautions would have to be taken to prevent it from "seeing" any specular material having a reflection factor greater than about 17% ($0.17 \times 15 \approx 2.5$ watts/cm^2/steradian--the damage threshold).

Corneal Reflection/Pupil Interference

If the corneal reflection falls near the boundary of the pupil, it will interfere with pupil tracking, because the corneal signal will be picked up as the aperture scans around the pupil. Likewise the pupil will interfere with the tracking of the corneal reflection. The general approach to be followed in overcoming this problem is:

1. The pupil video will be clamped to the mean tracking value whenever the pupil scanning aperture comes near to the corneal reflection (As in Figure 28). This involves loss of pupil information for a fraction of the available pupil scan, as shown in Figure 35.

2. By using a small scanning aperture the effect of the pupil, on the corneal tracking system is minimized.

Let g be the corneal tracking error due to a worst case of pupil interference. Let δ be the diameter of the scanning aperture. It may be assumed that the focusing system will maintain focus to a degree that the corneal reflection will appear to have a diameter δ, rather than its true (sharply focused) diameter ϵ. Let R be the relative intensity of the maximum pupil signal and sharply focused corneal reflection. Then

$$\text{(corneal signal)} = \frac{R\,\epsilon^2}{2} \text{ (pupil signal)}$$

and; $(\delta)(g)$ (corneal signal) $= 1/2 \cdot \delta^2$ (pupil signal),

$$\text{i.e., } g = \frac{\delta}{2} \left(\frac{\delta^2}{R\,\epsilon^2}\right) = \frac{\delta^3}{R\,\epsilon^2}$$

The minimum (worst case) value of R is about 40 and $\epsilon = 2.7$. The Oculometer scale factor is about 3×10^{-3} inches/degree

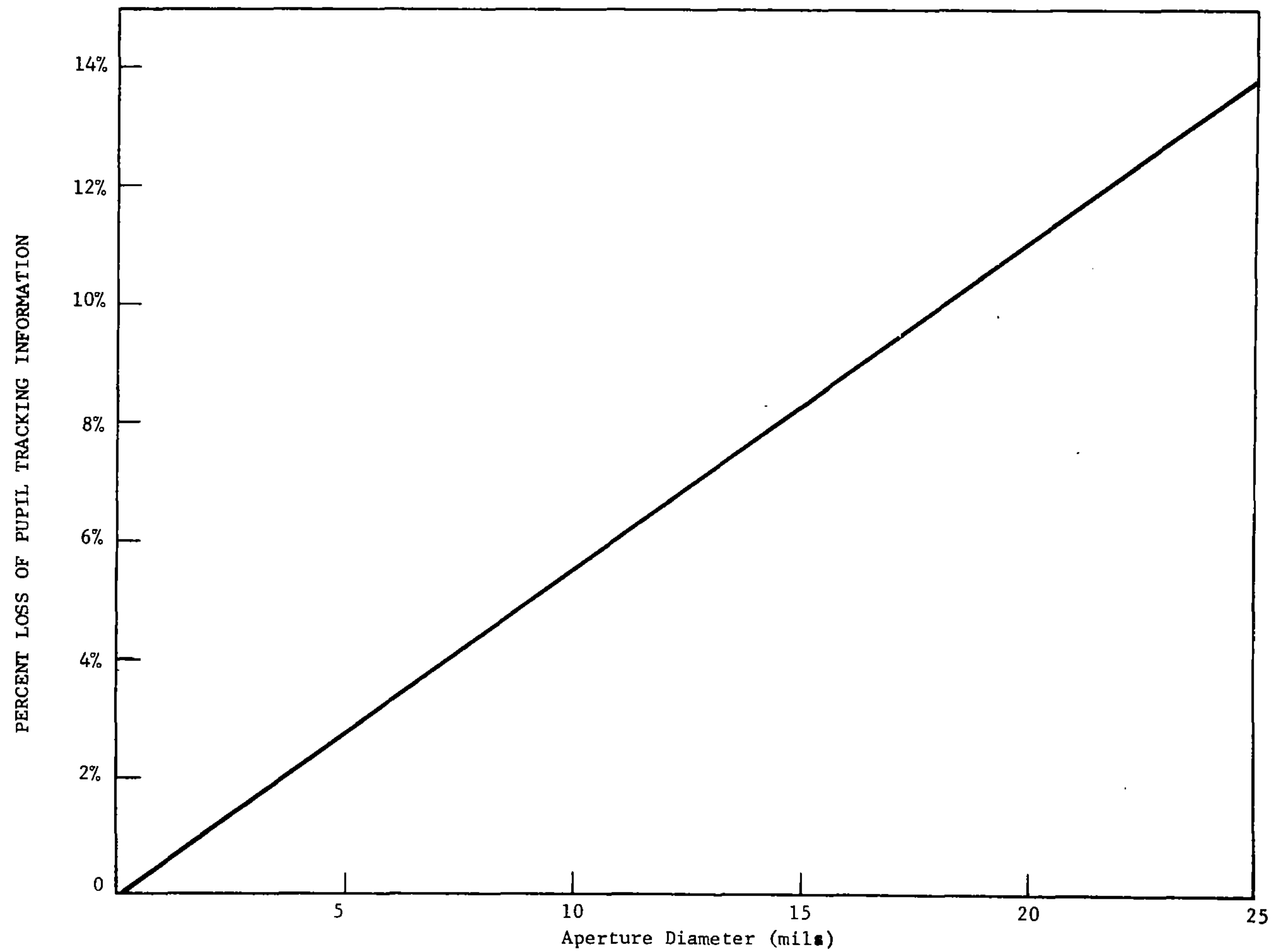


Figure 35 PERCENT LOSS OF PUPIL TRACKING INFORMATION

$$\text{Therefore, } g \text{ (in degrees)} = \frac{\delta^3}{40\ (2.7)^2 3} = \frac{\delta^3}{880}$$

where δ is in mils. This function is plotted in Figure 36.

Most of this error can be corrected out, since the position of the pupil/iris boundary relative to the corneal tracking scan is known at all times. It is reasonable to assume that such correction could compensate for at least 90% of the worst case error shown in Figure 36. Thus it should be easily possible to keep this particular error within 0.1 degree by using a 0.01 in. aperture (or smaller).

The Pupil Eccentricity Method of Measuring Eye Direction

A possible method of deriving eye direction information from the eye image is to measure the apparent eccentricity of the pupil image. When the eye is rotated away from the Oculometer axis, the Oculometer sees an oblique view of the pupil. The eccentricity of the pupil image is a function of the angular displacement of the eye, as discussed below. Let a pupil center at P be viewed from the point O (Figure 37). The point O is defined by the coordinates X Y relative to axes centered at Q where QP is normal to the pupil, and is of unit length. Consider any point, T, on the pupil boundary. The radius vector $\overrightarrow{PT}$ is given by

$$\overrightarrow{PT} = r \cos \psi \; \underset{\sim}{i} + r \sin \psi \; \underset{\sim}{i}$$

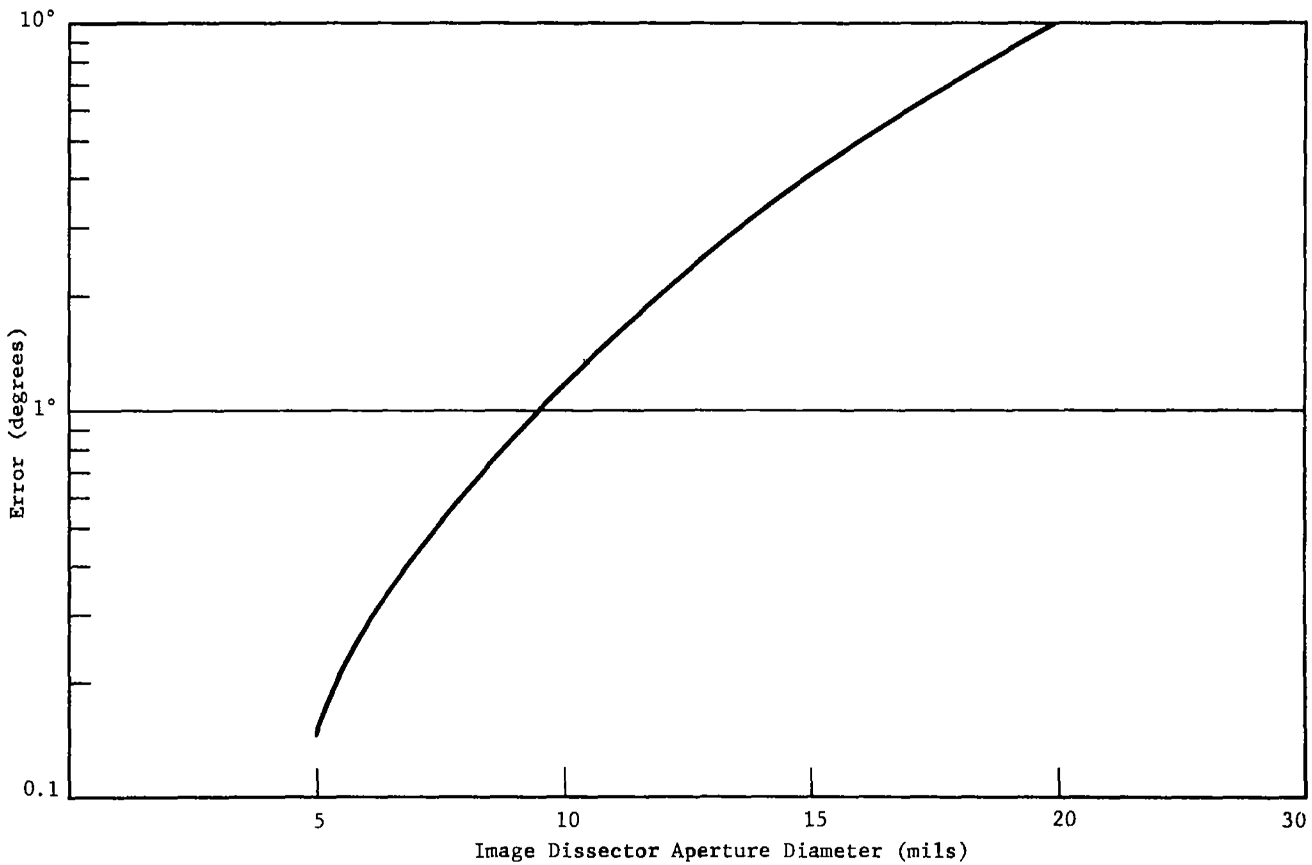


Figure 36 MAXIMUM UNCORRECTED ERROR DUE TO PUPIL INTERFERENCE WITH CORNEAL TRACKING

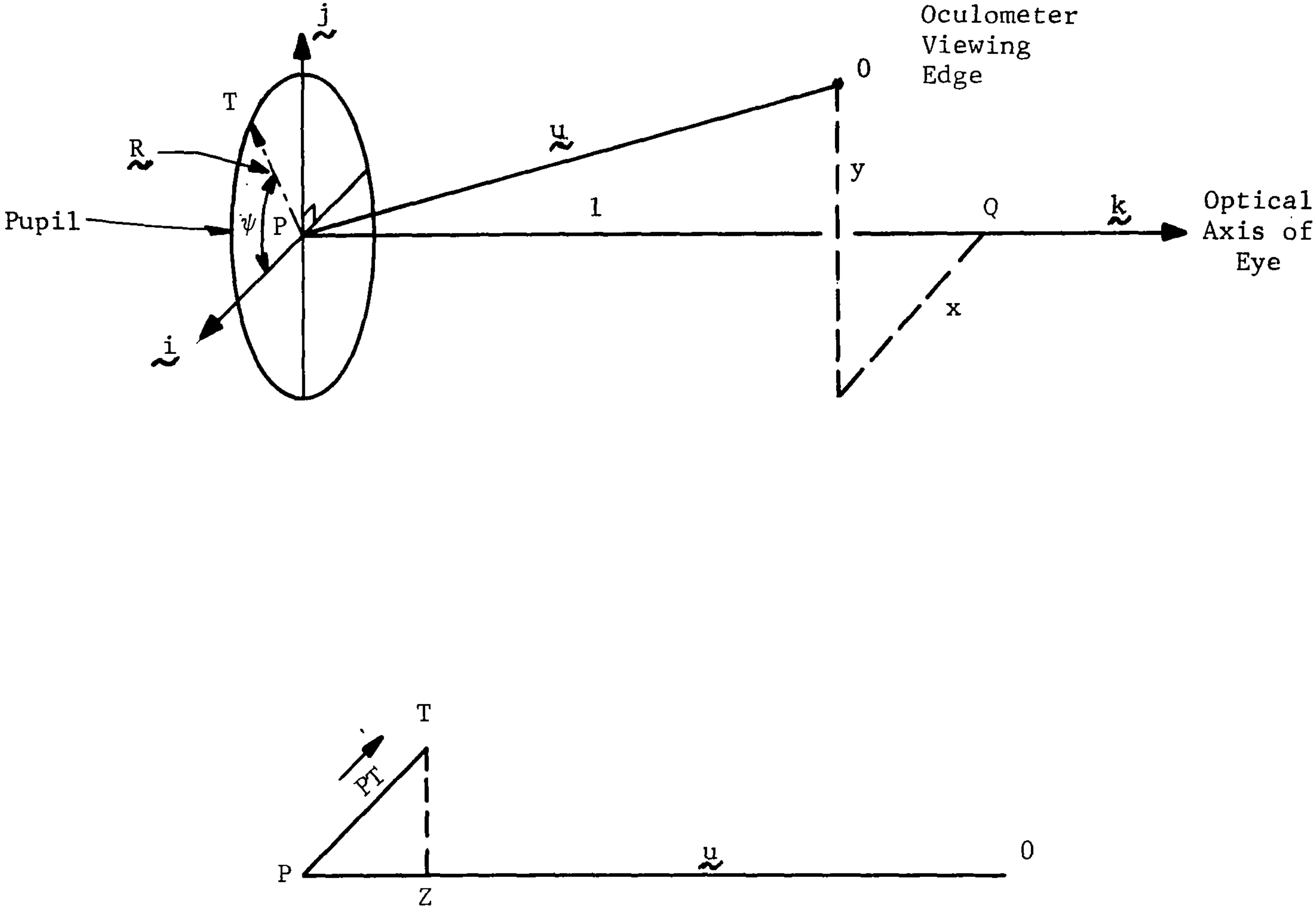


Figure 37 GEOMETRY OF ECCENTRIC TECHNIQUE

where ψ is the angular displacement of $\overrightarrow{PT}$ from the i direction.

Consider the projection (TZ) of $\overrightarrow{PT}$ onto a plane normal to OP:

$$\overrightarrow{TZ} = \overrightarrow{TP} - \overrightarrow{PZ}$$

$$= \overrightarrow{TP} - \frac{(TP\ \underline{u})\ \underline{u}}{|u|^2}$$

$$|TZ|^2 = |TP|^2 + \frac{(\overrightarrow{TP}\ \underline{u})^2}{|u|^2} - 2\ \frac{(\overrightarrow{TP}\ u)^2}{|u|^2}$$

$$= |TP|^2 - \frac{(\overrightarrow{TP}\ u)^2}{u^2}$$

$$= r^2 - r2\ \frac{(x \cos \psi + y \sin\psi)^2}{1 + x^2 + y^2}$$

$$= \frac{r^2}{1 + x^2 + y^2} \quad (1 + x^2 + y^2 - x^2 \cos^2 \psi - y^2 \sin^2 \psi -$$

$$2\ xy \sin \psi \quad \cos \psi)$$

$$= \frac{r^2}{1 + x^2 + y^2} \quad (1 + x^2 + y^2 - \frac{x^2}{2} (1 + \cos 2\psi) - \frac{y^2}{2} (1 - \cos 2\psi) - xy \sin 2\psi)$$

$$= \frac{r^2}{1 + x^2 + y^2} \quad (1 - \frac{x^2}{2} + \frac{y^2}{2} + \cos 2\psi\ \frac{(y^2 - x^2)}{} - xy \sin 2\psi)$$

$$(TZ) \approx r\ (1 - \frac{(x^2 + y^2)}{4} + \cos 2\psi\ \frac{(y^2 - x^2)}{4} - \frac{xy}{2} \sin 2\psi)$$

That is, the normalized radius vector contains two sinusoidal components, in quadrature of magnitude

$$u = \frac{x^2 - y^2}{4}$$

and

$$V = \frac{xy}{2}$$

In the pupil tracking system, these components may be recovered by appropriate demodulation. The demodulated signals may then be used to cause the addition of second harmonic components to the basic pupil circular scan in such a way as to cause pupil scan to match the elliptical pupil pattern. When the scans match there will be no second harmonic modulation of the video and no further addition of second harmonic components will be made to the circular scan. A measure of eye direction (x,y) may be derived from the values of the added second harmonic components (u,v) according to the equations given above, which can be solved to give

$$x^2 = 2 \left\{ u + \sqrt{u^2 + v^2} \right\}$$

$$y^2 = 2 \left\{ -u + \sqrt{u^2 + v^2} \right\}$$

Consider the effect (dx,dy) on x,y of errors (du,dv) in u and v

$$du = \frac{xdx - ydy}{2}$$

$$dv = \frac{xdy + ydx}{2}$$

$$dx = \frac{2(xdu + ydv)}{x^2 + y^2}$$

$$dy = \frac{2(xdv - ydu)}{x^2 + y^2}$$

Consider the case when the error in du, dv is equivalent to 1 mil, with a 40 mil radius (2mm diameter) pupil. Let $y = 0$, then

$$du = 1/40$$

and

$$dx = \frac{2\ du}{x} = \frac{1}{20x} \text{ radians}$$

Let θ_x be the angle x in degrees

i.e.,

$$\theta_x \approx 60x,\ d\theta_x = 60dx = \frac{60 \times 60}{20\theta_x} = \frac{180}{\theta_x}$$

For $\theta_x = 30°$, $d\theta x = 6°$ (for du, dv $\approx 10^{-3}$")

That is, the noise level of the eccentric technique will be about 18 times that of the regular method of measuring eye direction, when θ_x is 30°. For smaller values of θ_x the eccentric technique is even less accurate.

From the last column of Table I, and the analysis given above, it can be seen that the rms noise level with the eccentric method will be in the range of 0.9° to 6° depending on the relative Oculometer sensitivity.

Dynamic Characteristics of the Oculometer

The heart of the Oculometer is an electro-optical tracking system that is intended to follow certain pattern detail in the eye image. If there is any motion of the eye image detail relative to the sensor photocathode, there will, in general, be some tracking error; that is, the electro-optical tracking system will tend to lag behind the pattern detail that it is supposed to follow. The tracking system should, therefore, be designed so that the dynamic tracking errors, resulting from the expected range of eye image motions, are acceptably small.

Motion of the eye image in the Oculometer will occur with:

a. rotation of the eye
b. voluntary displacements of the head
c. involuntary displacements of the head caused by the environmental vibration.

A typical rotation motion of the eye is shown in Figure 38.

As discussed in another section, a two-axis moving mirror system is included in the remote Oculometer in order to maintain the eye image within about 0.25 in. of the center of the sensor

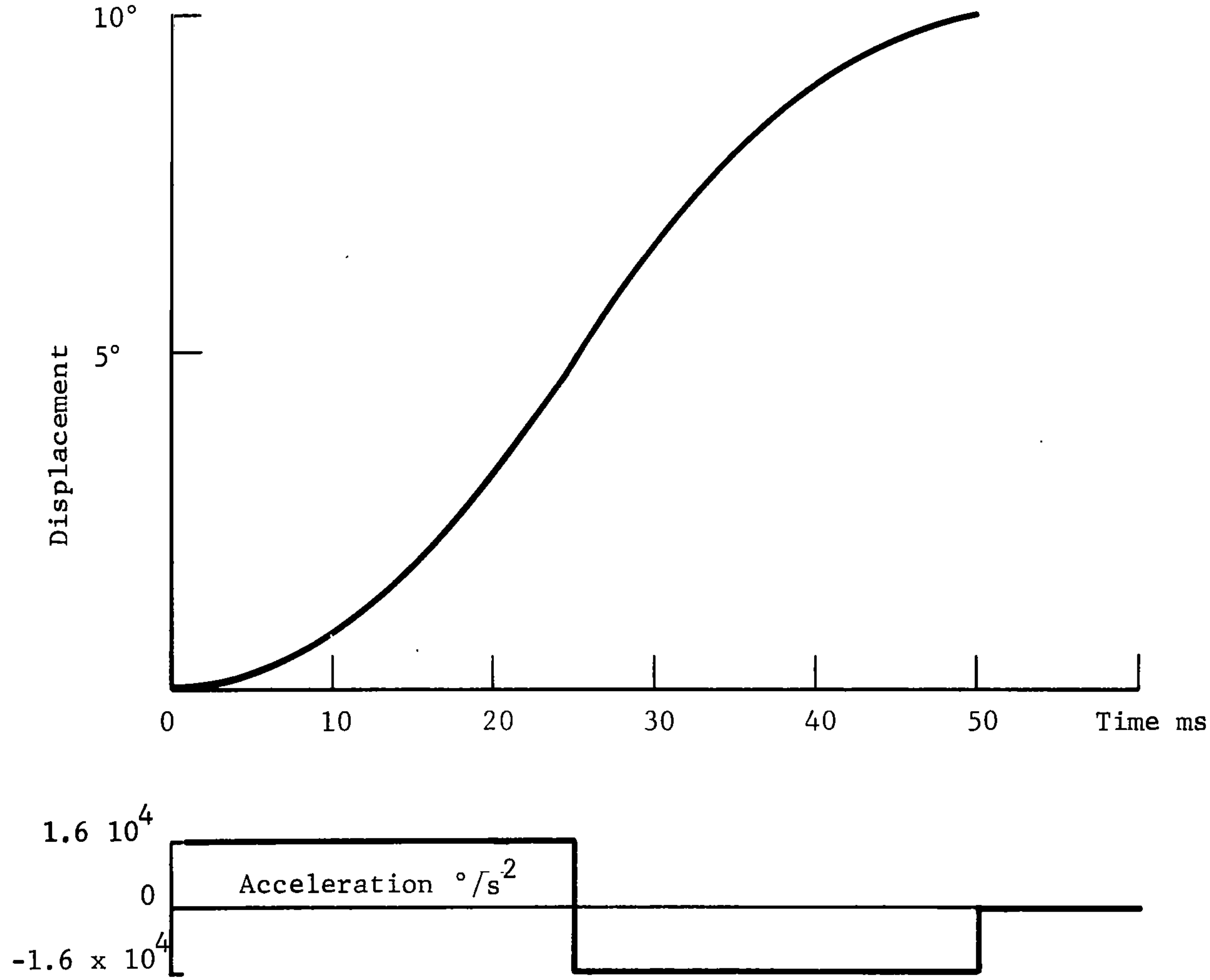


Figure 38 TYPICAL 10 DEGREE SACCADE IN 50 ms MAX. ACCELERATION = 16,000°/s^2 MAX.RATE = 400°/s

photocathode. The maximum voluntary motion (of type b, above) remaining after this servo mirror action will be 0.25 sin $4\pi t$ inches.

The distribution of typical aircraft vibration, and the human tolerance limits for vibration are shown in Figures 39 and 40.

The response of the Oculometer tracking system to these various motor inputs depends on the scan speed and also on the order of the tracking servo involved.

Single order servo tracking loops were used in the mental alertness Oculometer. (Figure 41a) A second order tracking loop is illustrated in Figure 41b. An important distinction between these two tracking loops is that the tracking error for a ramp input (i.e., $x = kt$) is ultimately zero for a second order system (Figure 42(c) and (d)) whereas, for a first order system, the tracking error rises exponentially to a nonzero steady state value (Figure 42(a) and (b)).

The amplitude response functions for the two types of tracking loops (based upon optimum damping and a 3 dB frequency of 80 Hz (or loop time constant of 2ms)) are plotted in Figure 43 for various environmental conditions.

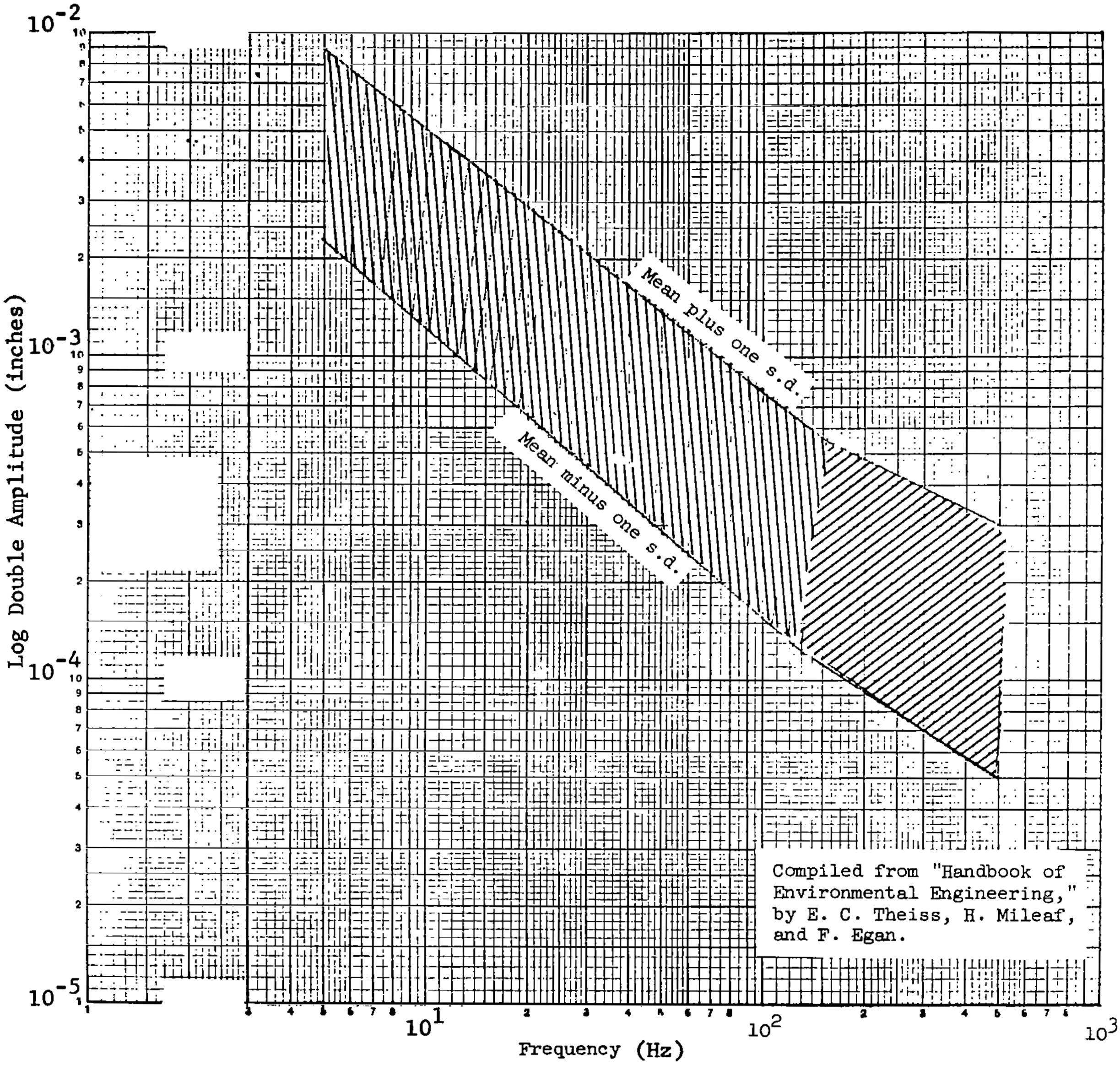
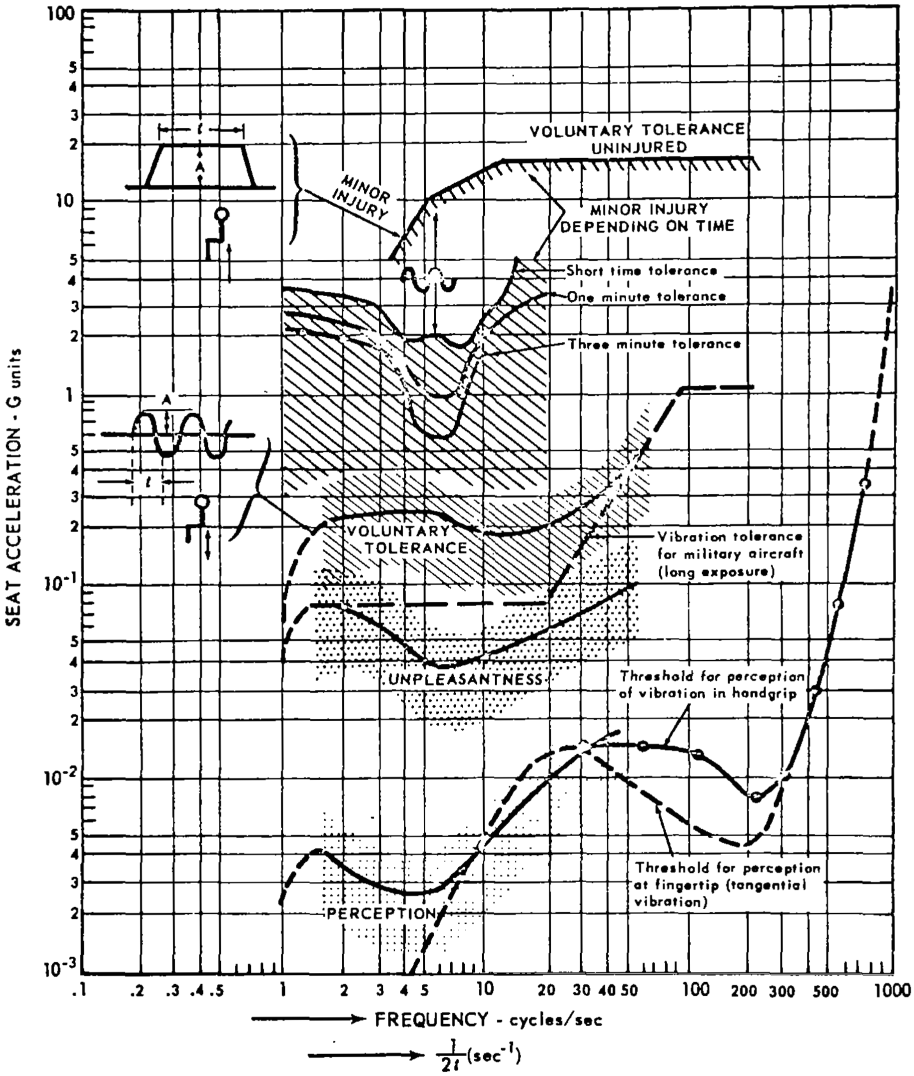


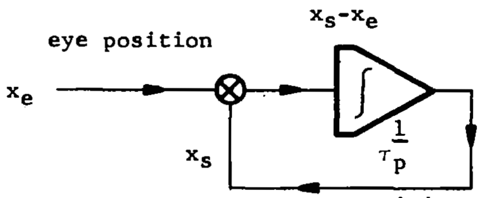
Figure 39 DISTRIBUTION OF TYPICAL AIRCRAFT VIBRATION

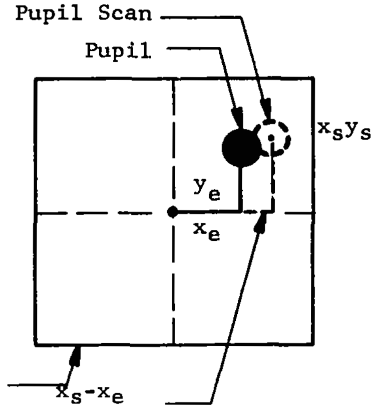


This illustrates schematically a number of tolerance criteria for vibration. The four shaded zones represent: threshold for perception; the unpleasant area of vibration; the limits of voluntary exposure, unprotected, for 5-20 minutes; and the voluntary tolerance limits for subjects with lap belt and shoulder harness for three minutes, one minute, and less than one minute. Above this, minor injuries occur, depending on time. At the top of the chart is plotted the voluntary tolerance curve for impact, which may be considered to be half-cycle vibration of large magnitude. The conventional way of measuring durations (t) and amplitudes (A) is shown in the small diagrams at the left.

Source: Adapted from von Gierke and Hiatt

Figure 40 CRITERIA FOR VIBRATION TOLERANCE





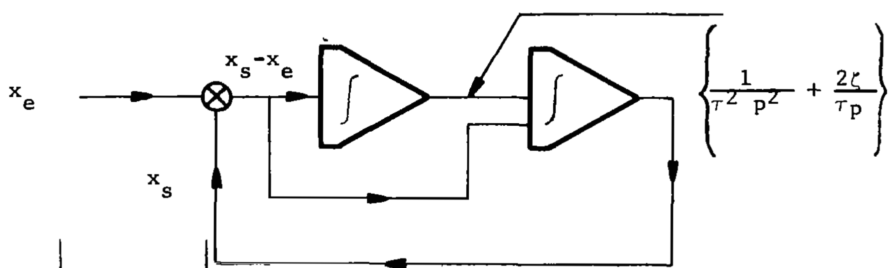
$x_s = \frac{-1}{\tau p}(x_s - x_e)$

$\therefore x_s = \frac{x_e}{1+\tau p}$

$\therefore x_e - x_s = \frac{x_e \tau p}{1+\tau p}$

$\frac{|x_e - x_s|}{|x_e|} = \frac{x}{\sqrt{1+x^2}}$ where $x = f/f_o$, $2\pi f_o \tau = 1$

Figure 41a FIRST ORDER TRACKING LOOP



$x_s = \left\{\frac{1}{\tau^2 p^2} + \frac{2\zeta}{\tau p}\right\}(x_s - x_e)$

$\therefore x_s = x_e \frac{(2\zeta\tau p + 1)}{1+2\zeta\tau p + \tau^2 p^2}$

$x_e - x_s = \frac{x_e \tau^2 p^2}{1 + 2\zeta p\tau + \tau^2 p^2}$

$\frac{|x_e - x_e|}{|x_e|} = \frac{x^2}{\sqrt{1 + x^4}}$ where $x = f/f_o$, $2\pi f_o \tau = 1$, $\zeta = \frac{1}{\sqrt{2}}$

Figure 41b SECOND ORDER TRACKING LOOP

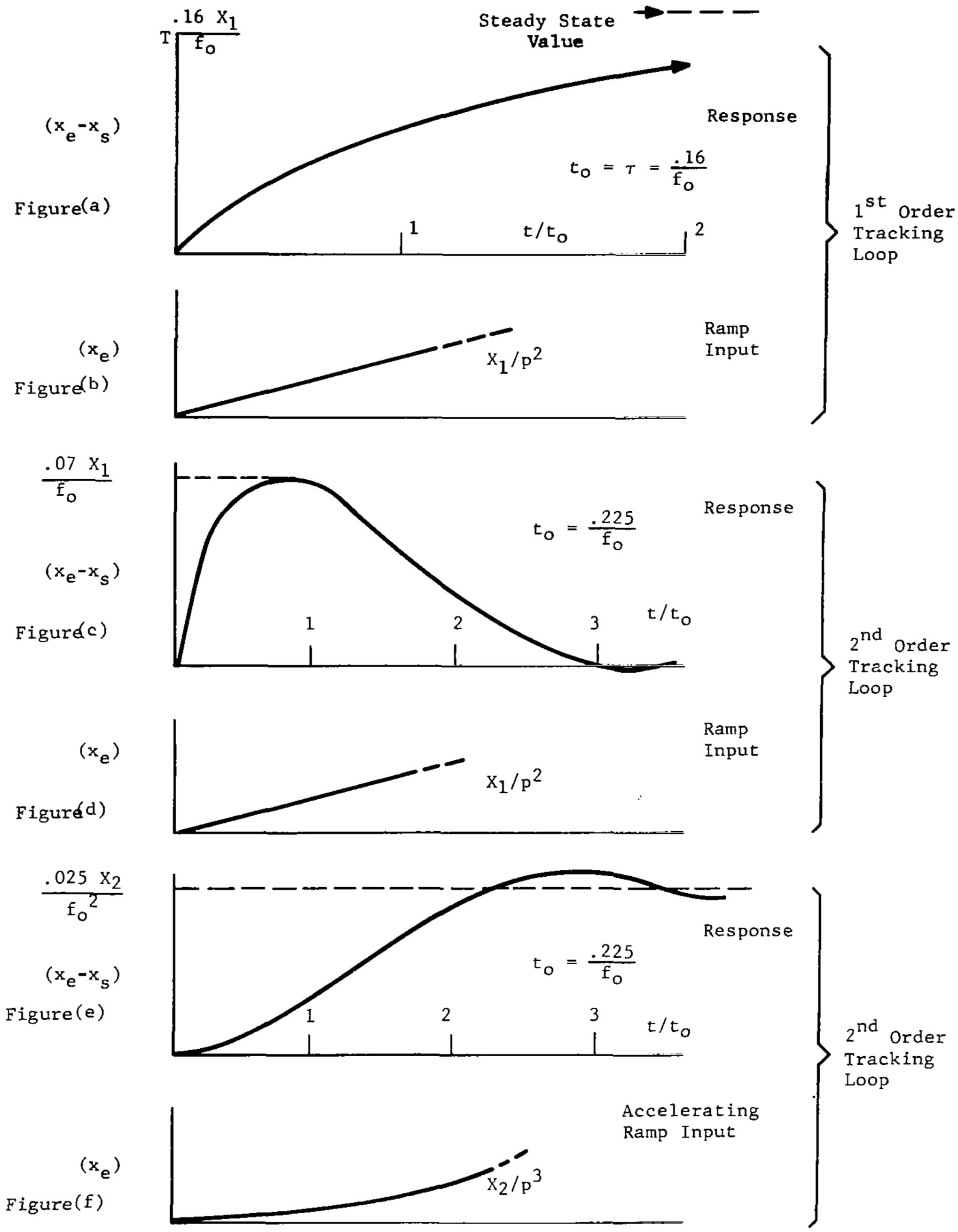


Figure 42 TRACKING LOOP RESPONSE FUNCTIONS

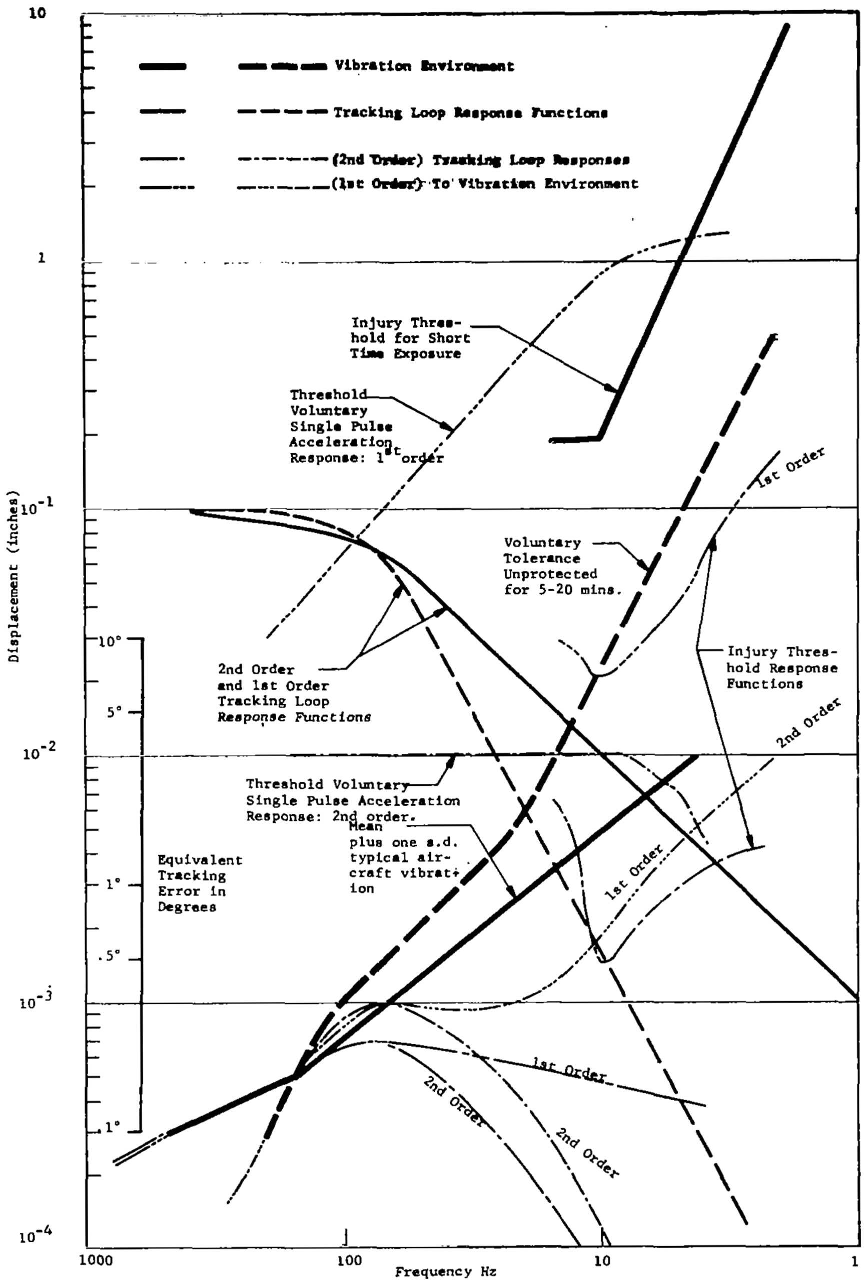


Figure 43 TRACKING ENVIRONMENTS AND RESPONSE

The system response to the maximum residual head motion ($0.25 \sin 4\pi t$) is

first order: 6.2×10^{-3} inches

second order 0.16×10^{-3} inches

Typical worst case eye motions are

$$\dot{\theta} = 400°/s, \ddot{\theta} = 16{,}000° /s^2$$

The first order response to a ramp of 400°/s (equivalent to 2 in/s of pupil motion) is (from Figure 42a),

$$2 \times 2 \times 10^{-3} = 4 \times 10^{-3} \text{ inches}$$

The second order tracking system yields a finite tracking error for an acceleration input, as indicated in Figures 42e and 42f. The peak tracking error in response to an acceleration of 16,000°/s^2 (equivalent to 80 in./s^2) is

$$\frac{0.025\ x_2}{f_0^{\,2}} = \frac{0.025\ t_o^{\,2}\ 80}{(0.225)^2} = \frac{0.025\ 4\ 80\ 10^{-6}}{(0.225)^2} \text{ inches}$$

$$= 0.16 \times 10^{-3} \text{ inches}$$

The first and second order system response to the typical eye motion rates are shown in Figure 44.

The results shown in Figures 43 and 44 show the expected magnitudes of the tracking errors under various conditions.

The next question to be considered is the magnitude of the dynamic tracking error that can be considered acceptable.

Tracking errors have two main effects:

a) If the dynamic tracking error is large enough the system will be forced out of its linear tracking range (Figure 45).

b) The instantaneous eye direction output will be in error if there is any differential dynamic tracking error between the pupil and corneal channels.

Errors of type (a) may cause loss of track if they are larger than the aperture diameter (for the corneal system) or larger then the pupil for the pupil system. Errors greater than the linear tracking range (Figure 45) will be corrected relatively sluggishly by the tracking system. Errors of type (a) and (b) will give rise to instantaneous errors in eye direction output. For random,

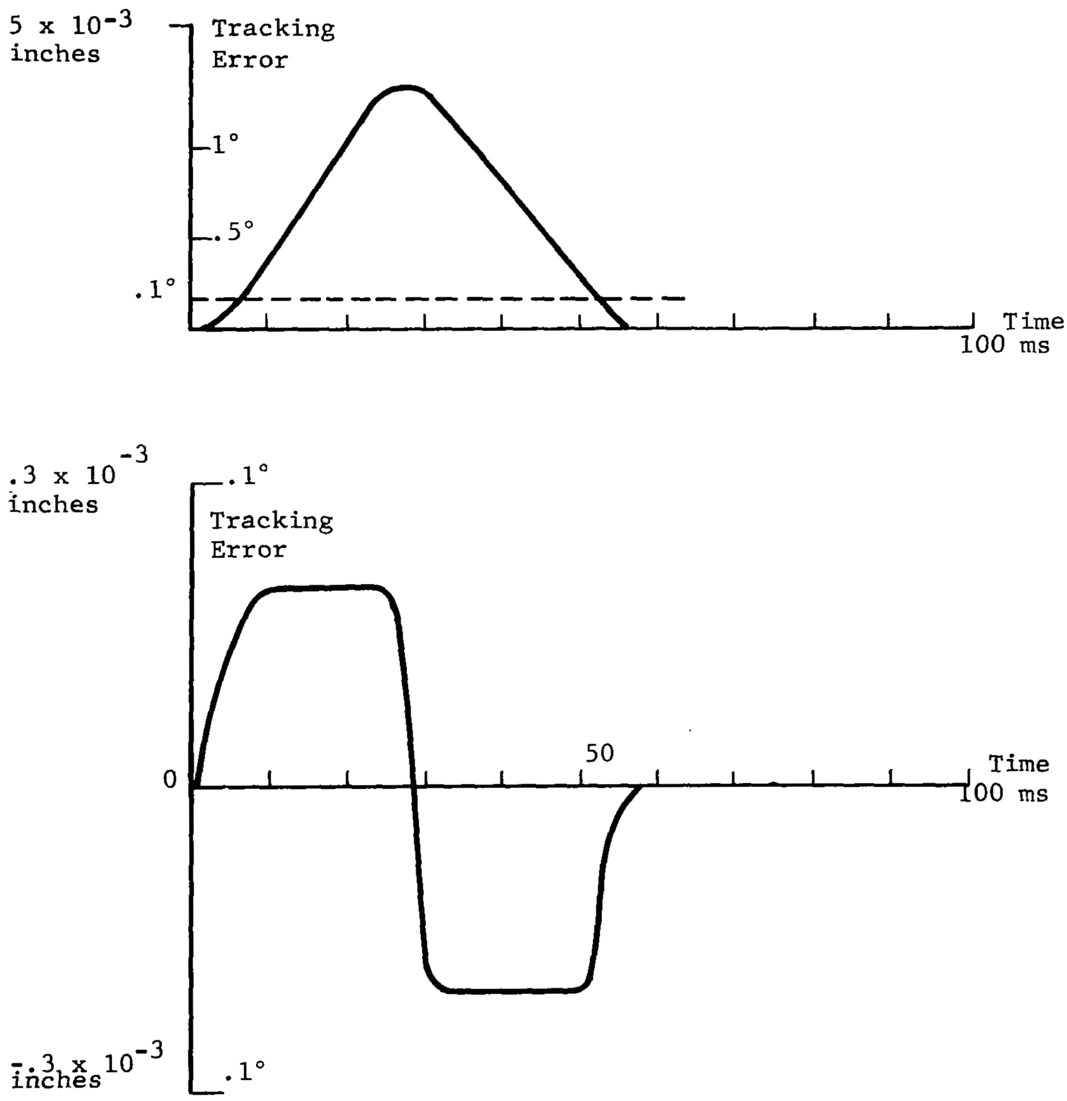


Figure 44 TRACKING ERROR RESPONSE TO TYPICAL RAPID EYE MOTION SHOWN IN FIGURE 38

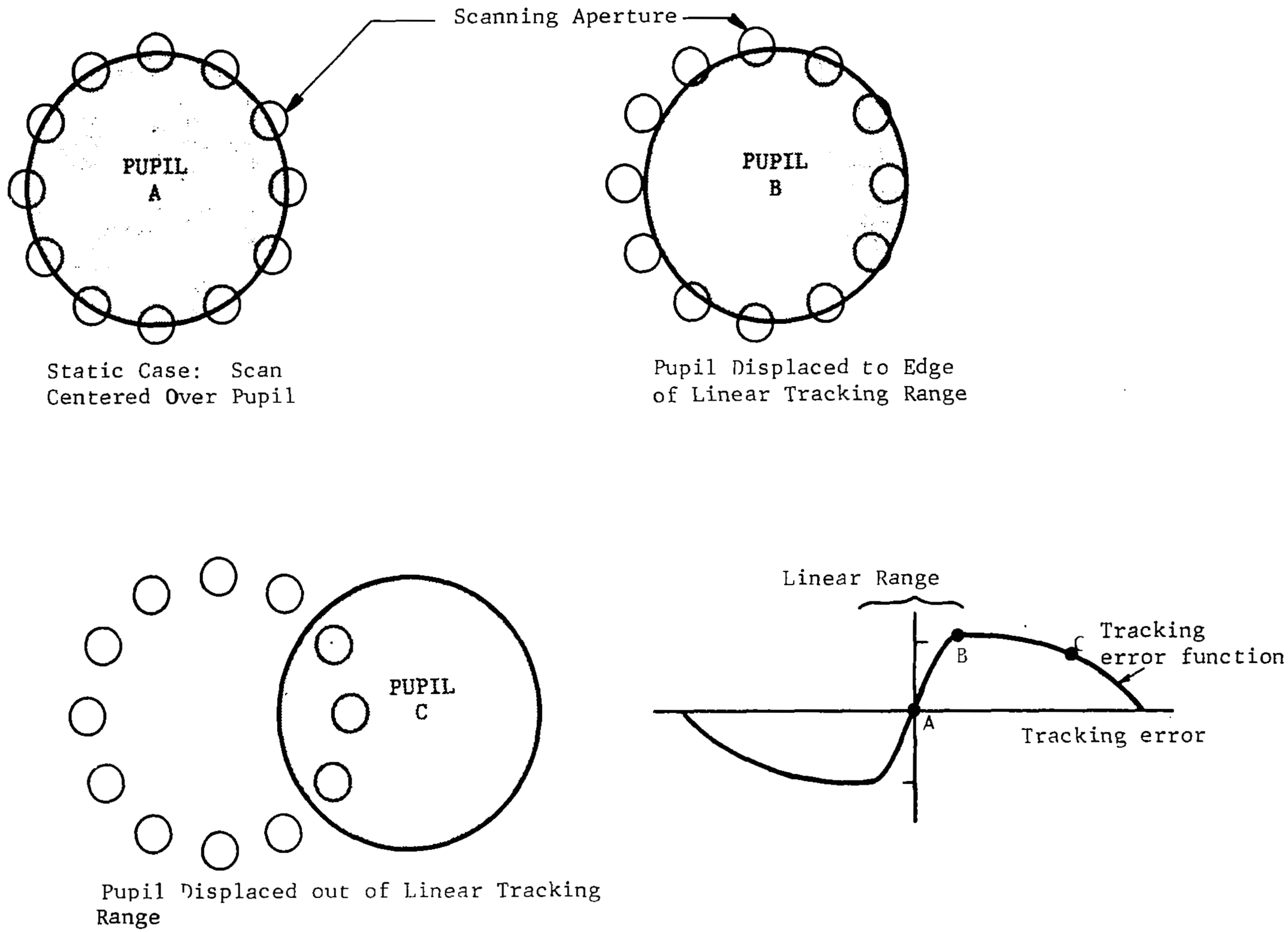


Figure 45 LINEAR TRACKING RANGE

high frequency vibration these latter errors may not be of great significance if they are less than, say 6×10^{-3} inches, since they will average out in any practical measure of eye direction.

The vibration and shock environments, in relation to these factors, are summarized in Table II.

It is evident that the 2nd order tracking system is very much superior to the first order. It imposes no restrictions on the choice of the aperture diameter except for extreme vibration and shock conditions.

The Electronic Signal

The minimum pupil signal output for a 20 mil aperture, for a tube gain of 3×10^6 and for a 50K Ω preamp load resistor is

$$V = \frac{1.6 \times 10^8}{400} \times 3 \times 10^6 \times 1.6 \times 10^{-19} \times 50 \times 10^3$$

$$\approx 10\text{mV}$$

A video bandwidth of about 100 kHz is desirable so that the system can respond, within a small fraction of a circular scan period, to the changing signal levels associated with the time division multiplex scan. The video signal/noise ratio is of the

Table II DESIGN CONSTRAINTS AND TRACKING ERRORS DUE TO MOTION AND VIBRATION ENVIRONMENT

MOTION VIBRATION ENVIRONMENT	FIRST ORDER TRACKING LOOP		SECOND ORDER TRACKING LOOP	
	Restriction or δ (aperture diameter in 10^{-3} inches)	Transient Errors	Restriction on δ (aperture diameter 10^{-3} inches)	Transient Errors
Eye Motion	>5	~1°	none*	<.1°
Voluntary Head Motion	>10	~2°	none*	<.1°
Mean Plus D Typical A/C Vibration	none*	~.2°	none*	~.2°
Voluntary Long Term Vibration Tolerance	<10	~3°	none*	~.2°
Injury Threshold -Short Term Exposure	Loss of Track for any δ	Loss of Track for any δ	>7	~3°
Voluntary Threshold Single Pulse Acceleration	Loss of Track for any δ	Loss of Track for any δ	>10	~3°

* none - means that vibration considerations do not impose any practical limitation and (i.e. other factors become dominant in the selection of δ)

order unity with this bandwidth; that is, each electron produces a pulse of the order of 0.10 mV. With a 5 mil aperture the electron pulses would still be 10 mV but the average signal level would be 0.6 mV. A gain of 16 would be required to bring the average level up to 10 mV. This would cause the peak pulse light to be 160 mV. Tracking loop circuitry can easily be assigned to handle these voltage levels. It is concluded, therefore, that as far as the electronic aspects of the problem are concerned, a 5 mil ID aperture can be used.

Moving Mirror System

The moving mirror system deploys the relatively small instantaneous field of view of the Oculometer over the larger total eye space region. In this way fine electronic tracking is used for following eye detail (down to 0.001 inch) whereas mechanical scanning is used to follow gross head motions.

The clear aperture of the mirror system will be of the order of 1/2 to 1 inch (determined by the range from eye to Oculometer (e.g., 30 inches) and the angular width of the Oculometer aperture at the eye (typically 1/2 to 1 degree). The dynamic range of the moving mirror system is defined by the desired height and width of the total eye space region, and by the range to the eye.

For example, with a nominal range to the eye of 4 feet and an eye space coverage of ±6 inches the angular range of the mirror need be only about ±3.5 degrees. The transient response of the mirror system must be such that the eye can be held in track within the useful photocathode area of the sensor tube for any naturally occuring head motion and also must be adequate for the execution of any search functions. The dynamic response of the mirror system is a function of the system inertia and motor torque.

Let I be the moment of inertia about one mirror axis. Let T_m be the peak torque of the motor. The response function is:

$$I\ddot{\theta} + k\dot{\theta} + h(\theta - \theta c) = 0$$

where k and h are constants and θ is the angular response of the mirror to a commanded position θc.

The torque actually applied by the motor is given by

$$T = I\ddot{\theta}$$

Rearranging the equations and selecting optimum damping:

$$\theta + 2\ \omega_n \dot{\theta} + \omega_n^2 (\theta - \theta c) = o$$

where ω_n is the 3dB angular frequency.

and then

$$k = \sqrt{2}\, I\, \omega_n$$

and

$$h = I\, \omega_n^{2}$$

The solution of the equation is:

$$\theta = \frac{\theta c}{(p^2/\omega_n^{2} + \sqrt{2}\, p/\omega_n + 1)}$$

In the case when the moving mirror assembly will be used to reflect the rays from the eye to an Oculometer mounted in front of the instrument panel (e.g., see Figure 56), the clear aperture of the mirror will be less than 1 inch in diameter. For a panel mounted system, the mirror aperture might be 2 inches. For the present purposes the mirror dimensions are assumed to be 2 x 1.5 x 0.25 inch.

The mirror will be mounted on a two axis gimbal system. The inner gimbal will cause the mirror to scan in the horizontal direction under the action of a torque motor (typically TQ-10W-1 Aeroflex) mounted on that gimbal.

The vertical scan motion will be controlled by a larger (e.g. TQ - 18-7) torque motor which will rotate, not only the mirror, but also the horizontal drive motor and inner gimbal yoke.

The total inertia about the vertical axis is then estimated as follows:

Horizontal Motor and Resolver		6.7×10^{-3} oz in. s^2
Horizontal Yoke		2.0×10^{-3}
Mirror		0.6×10^{-3}
Vertical Motor		0.7×10^{-3}
	Total	10.0×10^{-3} oz in. s^2

The inertia about the horizontal axis is simply that due to the mirror and motor, i.e., 1.3×10^{-3} oz in. s^2.

The angular displacement of the mirror (to cover ±6 inches at 4 feet) is only ±3.5 degrees. The maximum open loop frequencies (ω_m) (for these displacements) may be calculated from the equation

$$T_m = I\ddot{\theta}$$

where $\theta = 3.5° \sin \omega_m t$

$= 0.6 \sin \omega_m t$ (radians)

$\therefore \quad T_m = .06\, \omega_m^2\, I$

$$\therefore \quad \omega_m = \sqrt{\frac{Tm}{.06\ I}}$$

$$= \sqrt{\frac{1}{(06)(1.3)(10^{-3})}} \qquad \text{horizontal axis}$$

$$= \sqrt{\frac{20}{.06\ (10)(10^{-3})}} \qquad \text{vertical axis}$$

= 113 radians/s (18 Hz) horizontal

= 182 radians/s (30 Hz) vertically

The actual 3 dB frequency may be calculated from the value of the largest amplitude step displacement $\Delta\theta$ for which linear closed loop tracking is required. This can be specified in terms of typical rapid eye displacement i.e., $\Delta\theta \approx$ 0.2 inch at 50 inches $\approx$ 0.25 degree = 4×10^{-3} radians

Then

$$h = \frac{1.0}{4 \times 10^{-3}} \qquad \text{(horizontal axis)}$$

$$= 2.5 \times 10^{2} \qquad \text{oz in./radian}$$

$$\omega_n = \frac{1.2 \times 10}{3.6 \times 10^{-2}}$$

$$\omega_n \approx 3.3 \times 10^2 \qquad \text{radians/s}$$

and

$$h = \frac{20}{4 \times 10^{-3}} \qquad \text{(vertical axis)}$$

$$= 5 \times 10^3 \qquad \text{oz in/radian}$$

$$\omega_n = \frac{70}{10^{-1}}$$

$$= 7 \times 10^2 \qquad \text{radians/s}$$

These frequencies are more than adequate to cover any degree of head motion.

Acquisition

The Oculometer must initially search for the eye. The total eye space volume (in which the eye may be placed) is very large compared to the area that is sampled instantaneously in the normal tracking mode (e.g., two cubic feet compared to 0.01 cubic inch). There are three main problems associated with the scan and acquisition process.

(1) The finite speed of response of the mechanically scanned elements of the system (i.e., the moving mirror and the auto-focusing system).

(2) The limited intensity (in photons/s) of the detail to be acquired, which requires that the Oculometer sensor dwell over each small region of the eye space long enough for it to pick up a significant number of photons in order to sense if an eye is at this point.

(3) The discrimination of the eye detail from any other detail that may exist within the total eye space.

Taking item (3) first: the scanning aperture of the image dissector may, in the search mode, pass over highly specularly reflecting detail (e.g., tie clip). This will produce a larger signal than that of the eye. Also for small pupils, and relatively small values of the Oculometer F/number (e.g., 30-50), the contrast between the pupil and a white diffuse reflector (e.g., shirt, skin etc) may not be sufficient for simple reliable acquisition.

There are two possible approaches to this problem

(1) Use a special head marker located near the eye, for unique initial acquisition and then deflect the sensor by

a preprogrammed amount towards the eye. It will then be sufficiently close to the eye so that unique eye acquisition can be achieved relatively easily.

(2) Use a special logical criteria for acquisition, rather than a simple amplitude criterion. For example acquisition could be signalled if, and only if, the signal at points A and D, is below a certain threshold (corresponding to the iris) while the signal at point B is above another threshold (corresponding to the pupil) - -where the points A B C are along a horizontal raster line separated by 0.3 in. each.

The moving mirror system described previously can deploy a 1 in. x 1 in. instantaneous field of view over the total eye space (12 in. x 12 in.) in about 0.2 second (based upon the 30 Hz maximum mirror horizontal scan rate) (Note that this time could be reduced by using smaller mirrors). Assuming a 0.005 in. image dissector aperture is used with an F/50 Oculometer optical system, the maximum depth of focus for seeing the pupil would be only about ±2 in. For a total range uncertainty of ±12 in. search (in x,y) six different times, each with a new setting of the focus range. This would give a maximum initial acquisition time of 1.2 seconds.

A minimum pupil signal (with the minimum Bsti value of 1.5W, cm^2/ster) will require about 0.1 second for electronic search for one $in.^2$ of instantaneous eye space, with a 0.005 in. diameter image dissector aperture. Thus without a head marker (and with the other system parameters as previously assumed) the time required to search the entire eye space region for the pupil would be 144 x 6 x 0.1 = 86.4 seconds. That is acquisition time, in this case, is limited by the signal, not the mechanical inertia of mirror system. For more rapid acquisition a head marker should be used. The head marker can consist of an area of about one $in.^2$ of corner reflecting material. The intensity of the return from this material will be at least equal to that from the corneal reflection - but will of course extend over a larger area. On this basis the time required to receive a significant number of photoelectrons (e.g.,10) will be given by:

$$T x \frac{6 \times 10^{10}}{80 \times 80} = 10$$

i.e.,

$$T = \frac{6.4 \ 10^4}{6 \times 10^{10}} \approx 1 \mu s$$

This time is so small, compared to the time that will be taken to deflect the mirror over the head marker area (i.e., about 2 milliseconds) that a very high threshold can be set for acquisition.

Acquisition time, in this case, is limited by the mirror inertia (not signal) Because of the relatively large area of the head marker this acquisition system will have an excellent depth of focus (e.g., at least ±25 in. with an F/50 system). Thus for initial acquisition the focusing servo can be kept set at mid range.

Once the head marker has been acquired, the focusing servo will be activated to bring it to sharp focus, and then the moving mirror will be deflected (by a preprogrammed amount) to the region of the eye, where a purely electronic search will be initiated for the pupil.

The total sequence of events in the acquisition mode is given in Table III

The Optical System

This section covers the conceptual design of the illumination and collection optics for a panel mounted Oculometer and a roof mounted Oculometer. The requirements for the illumination optics are as follows:

(a) Approximately one inch of eye space coverage with uniform irradiation for reliable acquisition from a helmet marker.

Table III ACQUISITION MODE SEQUENCE

EVENT	MIRROR ACTION	FOCUS SERVO ACTION	TIME	ELECTRONIC ACTION
1. Nothing in eye space	Raster search over all of eye space	Fixed at mid range	0.2s per raster frame	Video Level analyzed
2. Head placed in eye space	Search stopped. Mirror held at acquisition position	Servos to sharp focus of marker	0.1s	Large return from head marker detected
3. After (2)	Mirror deflected to eye	Fixed at previous best focus position	0.1s	Electronic pupil search initiated and video level analyzed
4. After (3)	Mirror tracks pupil	Servos to sharp focus of pupil	0.03s	Pupil detected pupil scan initiated video level analyzed
5. After (4)	Mirror tracks pupil	Servos to sharp focus of corneal reflection	0.1s	Corneal reflection acquired. Normal Oculometer tracking
6. Blink	Held in last track position for 1.0s	Held in last track position for 0.2s	0.1s or less	Same as (3)
7. Blink persists for longer than 1s	Revert to 1	Revert to 1	Revert to 1	Revert to 1

(b) Apparent size of the light source at the eye is to be one degree for F/50 optics.

(c) Apparent light source will be about 48 inches from the eye by specification.

(d) Size of illumination optics is to be minimized.

The requirements for the collection optics are similarly listed as:

(a) The F/number of the collection system will be about 50 (for example 1 in. diameter lens at 48 in. object distance) for maximum pupil iris contrast.

(b) The image of eye space is to be focusable on the photocathode for object distances of 48 in. ± 12 in. by specification.

(c) The eye space coverage will have a one-inch diameter with approximately one to one magnification for reliable acquisition from a helmet marker.

(d) The change in net magnification with focusing adjustment should not be excessive and, if possible, linear to assist in electronic processing to eliminate the phenomenon.

(e) The imaging should be of good quality (small blur circle, less than 1% distortion).

(f) The size of the collection optics is to be minimized.

Optics Mounted in Panel In the first case, the illumination and collection optics are truly mounted in the cockpit instrument panel.

Collection Optics In this case, the collection optics are of simple telephoto construction as shown in Figure 46. Focusing is obtained by varying the position of the negative lens. Lens parameters for two practical collection systems are shown in Table IV.

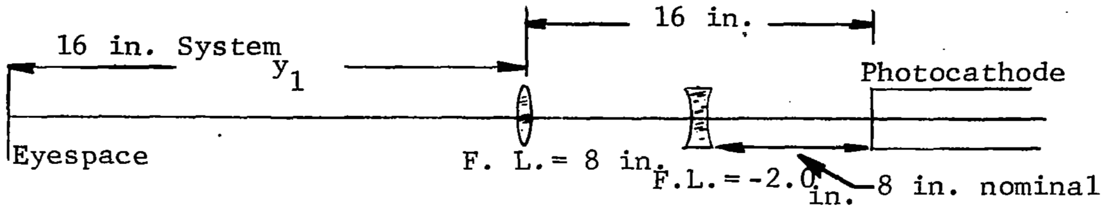
A. Illumination Optics The illumination optics for the "in panel" case is shown schematically in Figure 47. Lenses L_1 and L_2 image the light source onto the lens L_3. Lens L_1 is imaged onto the eye space.

The relevant lens parameters are shown in the figure. It is assumed that the arc is 0.033 inches in diameter. Thus the 30x magnification allows it to totally fill the lens L_3. The apparent size of the source image to the eye will be F/50 (1 in. source at 48 in. distance). The size of lens L_1 is 0.6 inches in diameter; it is imaged onto eye space with 1.6x magnification, thereby yielding approximately 1-inch diameter eye space coverage.

Table IV

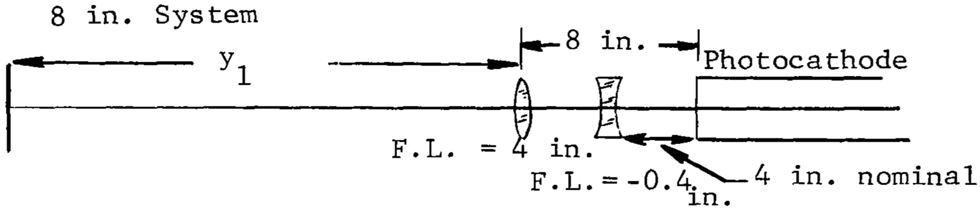
LENS PARAMETERS FOR TWO PRACTICAL COLLECTION SYSTEMS

a) 16 in. System



Object Distance y. (in.)	Net Magnification	Change in Negative Lens Position (in.)
60	0.80	-0.42
54	0.89	-0.20
48	1.00	0.00
42	1.14	+0.32
36	1.32	+0.69

b) 8 in. System



Object Distance y. (in.)	Net Magnification	Change in Negative Lens Position (in.)
60	0.82	-0.15
54	0.90	-0.04
48	1.00	0.00
42	1.15	+0.06
36	1.34	+0.14

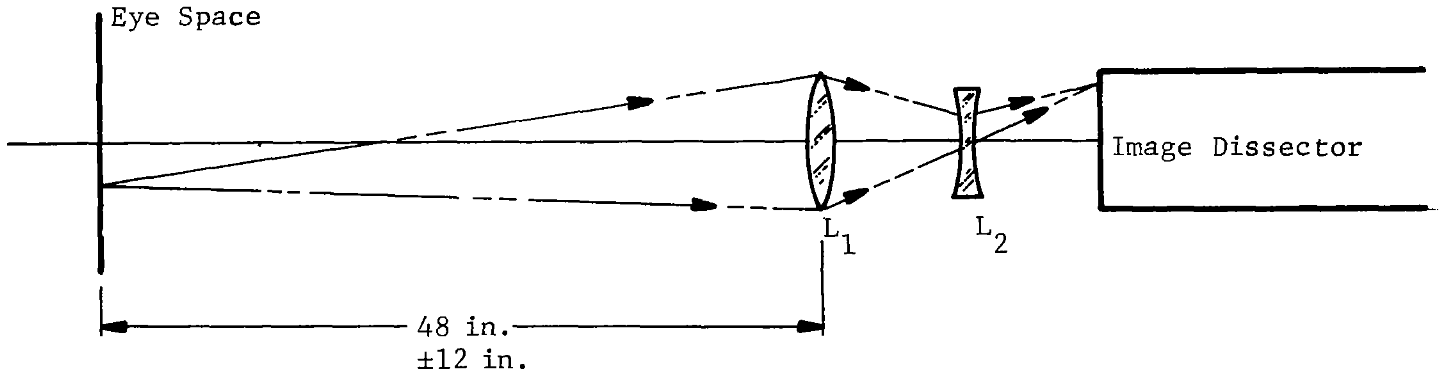
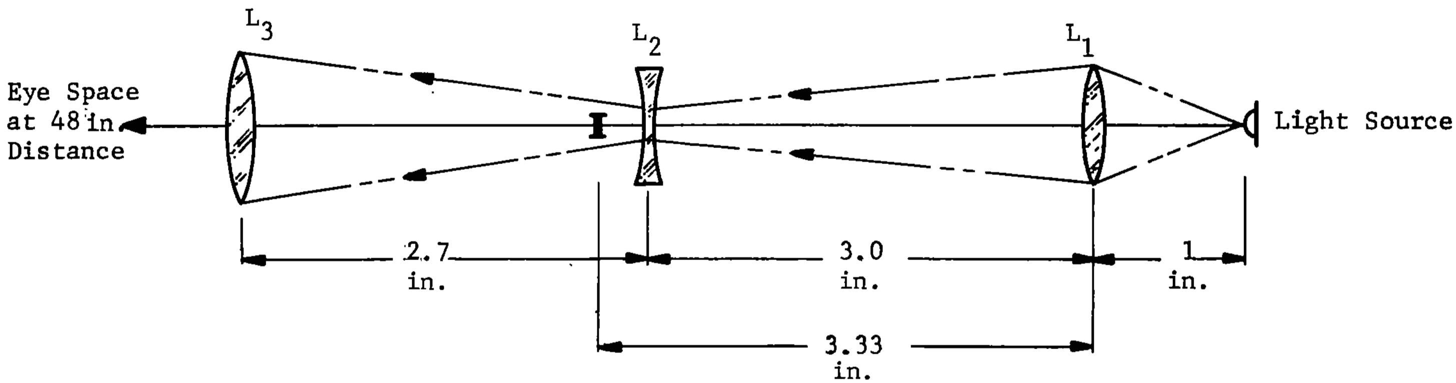


Figure 46 PANEL MOUNTED COLLECTION OPTICS



L_3 is 1.0 in. diameter and 2.82 in. focal length

L_2 is -1/3 inch focal length and approximately 0.1 in. diameter

L_1 is 0.6 in. diameter and 0.77 in. focal length

L_2 and L_1 image source onto L_3 with 30x magnification

L_3 and L_2 image L_1 onto eye space with 1.67 x magnification

Figure 47 "IN PANEL" ILLUMINATION OPTICS

It should be noted that in order to insure uniformity of illumination in the eye space due to axial head motion it may be necessary to increase the diameter of lens L_1 to one inch.

The quality of the imaging for the illumination optics need not be high, and can be easily fulfilled with this system.

B. Focusing System The focusing of the optics for this configuration is obtained by varying the position of the negative lens. The mild exponential change in magnification due to focusing from 36 to 60 inches with this scheme can be approximated as a linear function and thus eliminated by electronic processing.

Both magnitude and direction are necessary to establish how to appropriately move the negative lens to acquire focus. Thus a 2 stage focusing technique is required.

1. The maximum amount of motion necessary to acquire focus of a 16 in. telephoto lens system would involve a 1 in. displacement of the concave element as indicated in Table IV. If the subject accelerates at a rate of 1 g over a 1/2 foot the maximum velocity attained would be 5.6 ft/s. This would correspond from Table IV to a lens motion of 3 in./s which can be initiated by a rack and pinion drive or worm gear drive.

2. The direction of motion necessary to focus the image can be obtained by a dither about the focus. For an F/50 system with a 5 mil aperture, the blur circle would be 5 mils if the focus changed ± 1/8 in. Thus a 1/4 in. dither path would sufficiently blur the image of the corneal highlight so as to be detectable during the tracking mode. One half of a cycle of this dither should occur in the time taken for the concave focusing lens to move 1/8 in. at a 3 in./s rate. This corresponds to a rate of 12 Hz which can be implemented by a spring loaded, cam operated sleeve on the rack and pinion mentioned above.

It should be noted that if the 8 in. system (Table IV b) were used, the smaller required negative lens motion would allow a slower velocity focusing system.

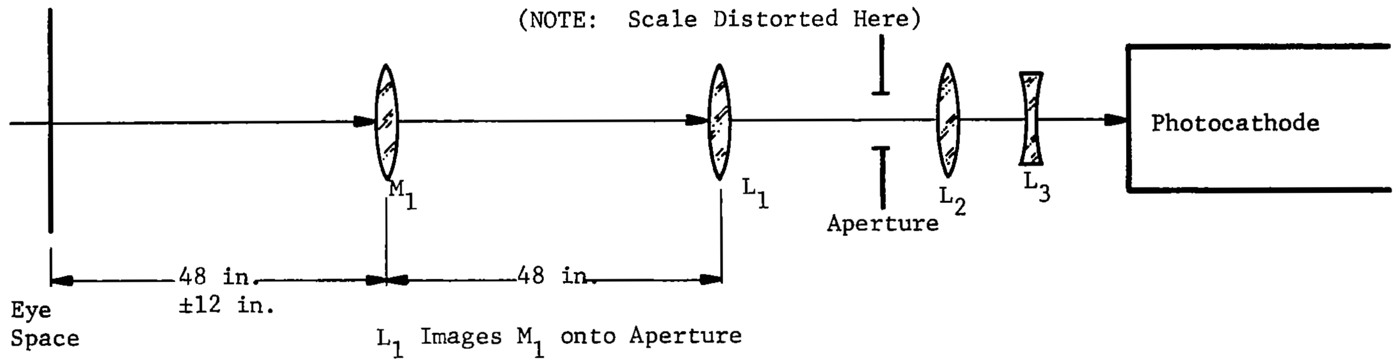
Optics Mounted Above or to Side of Pilot In the second case, a rotating spherical mirror is mounted in the panel; this mirror directs radiation to and from optics mounted above or to the side of the subject (pilot).

A. Collection Optics The layout of this optics system relative to the cockpit is shown in Figure 52. A moving mirror is placed in the cockpit panel; the curvature and orientation of the mirror are such that it causes an image of eye space to be formed in the vicinity of refractive optics located above or to the side of the pilot. The refractive optics then relay that image onto the photocathode.

The refractive optics are shown schematically in Figure 48. Lens L_1 images the mirror into the aperture shown; this aperture insures that only rays from the eye space reach the photocathode. Axial motion of negative lens L_3 creates a focusing adjustment. It is assumed that the distance between L_1 and M_1 is fixed at 48 inches. The distance between M_1 and the eye is variable from 36 to 60 inches.

Figure 49 shows lens parameters for a practical optical system of this type. In the data shown the magnification varies between 0.84 and 0.70 as the focusing lens L_3 is moved over a total range of 3.6 inches. The variation of magnification with range is not at all linear, so that in this case a rather sophisticated output linearization circuit would have to be designed. However, appropriate modification of some of the lens parameters in the system might make the magnification variation somewhat more linear.

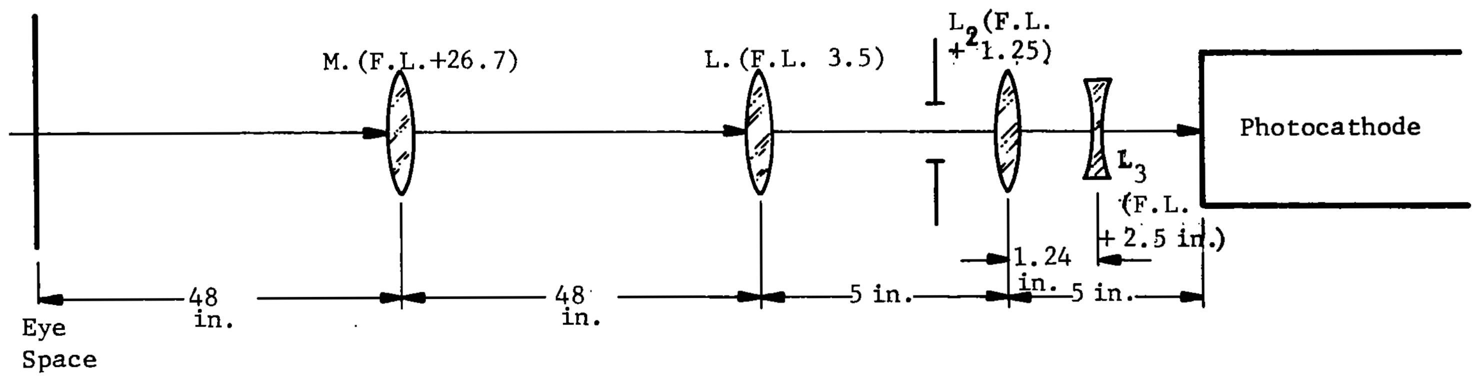
The total refractive system length (in Figure 49) is ten inches. It is probably possible to reduce that length still further without appreciably degrading image quality.



L_1 Images M_1 onto Aperture

L_1, L_2, L_3, and M_1 image eye space onto Photocathode

Figure 48 LAYOUT OF "ABOVE HEAD" OPTICAL SYSTEM (COLLECTION)



OBJECT DISTANCE (in.)	MAGNIFICATION (NET)	CHANGE IN POSITION OF L_3 (in.)
60	0.80	1.24
54	0.821	0.69
48	0.835	0.00
42	0.840	-1.04
36	0.70	-2.36

Figure 49 PRACTICAL COLLECTION OPTICAL SYSTEM (ABOVE PILOT)

B. Illumination Scheme The illumination scheme is, in this case, quite simple. As shown in Figure 50, a positive lens (L_1) images the object (light source) onto the moving mirror. The moving mirror then images the lens L_1 onto the eye space such that at least 1 in. of eye space is covered.

Electro-Optical Sensor

An image dissector such as the Oculometer image sensor leads inevitably to a theoretically low sensitivity because of the inherent nonstorage operation of the image dissector. Thus, suppose a 5 mil sampling aperture is used in tracking the 0.7 in. circumference of the pupil. At any instant, photoelectrons are received from only a small fraction (5/700) of the total circumference of the pupil border. Thus about 99% of the theoretically available signal is lost due to the nonstorage operation of the tube.

Considerable thought has been given to the possible means of overcoming this problem. Unfortunately conventional storage tubes (e.g., SEC tubes) lose in sensitivity more than they gain (in the present application) by their storage operation (e.g., the Westinghouse WL 30691 SEC tube can detect a minimum signal of 3000 photons, even though its S20 photocathode has a normal quantum efficiency of 0.20. That is, the effective sensitivity of the tube

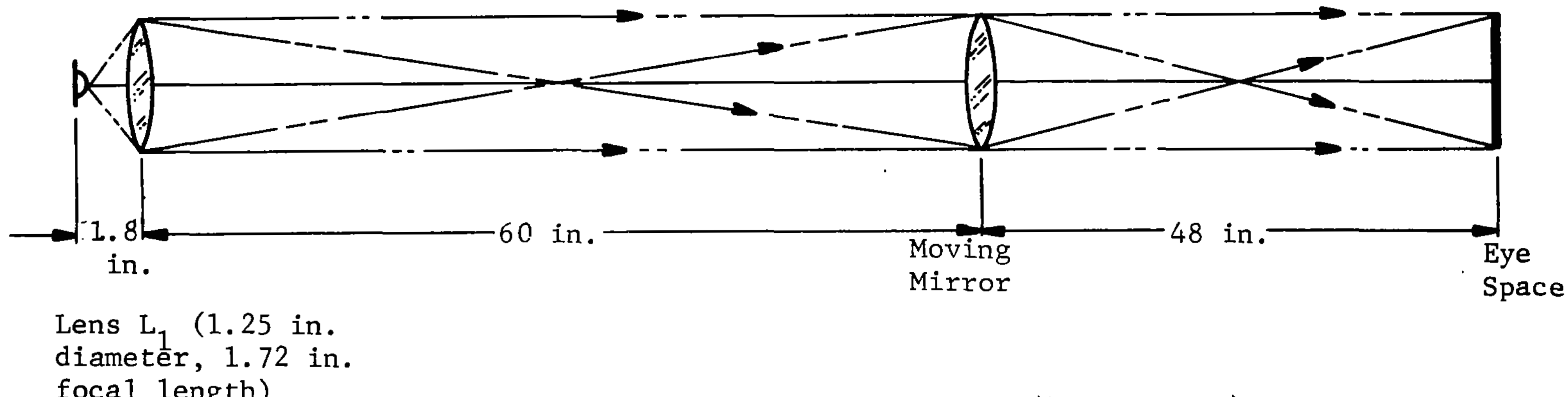


Figure 50 ILLUMINATION SCHEME (ABOVE PILOT)

appears to be 600 times less than that of its photocathode). In conventional (i.e., TV) applications this loss of sensitivity is relatively unimportant compared to the benefit of storage operation, which for a 500 line TV system, is a factor of 250,000. For the Oculometer, on the other hand, the loss due to nonstorage operation is only a factor of 100. So that the 600 times loss of the tube is dominant.

A conceptually very attractive solution to the sensor problem is the use of an image intensifier in front of the image dissector. The intensifier would have an S1 or S25 photocathode and a photon gain (at the phosphor) of at least 500.

The phosphor on the intensifier screen would be chosen so that its time constant was of the same order as the Oculometer scan (i.e., 1 millisecond). The 500 photons generated by the phosphor through the emission of a single photoelectron from a point x on the intensifier photocathode would be emitted in a random sequence over a period of about 1 millisecond. The dissector (which in this case would have an S20 photocathode) would then be able to generate a single photoelectron even though its aperture would dwell over the point corresponding to X for only $\frac{1}{100}$ of a millisecond. In other words a 5 mil dissector aperture could scan around a pupil image and detect almost every theoretically available photoelectron. The phosphor, of the preceding intensifier tube, would have converted the normally nonstorage dissector to, effectively, stoarge operation. A single envelope tube of this type, known as the Image Dissecticon, has been made by the Bendix Research Laboratories for NOL Corona.

However, as described in the section on photocathode damage, this type of tube must be rejected, in most cases, because of the potential photocathode damage that could be caused by highly specularly reflecting surfaces.

Therefore, the best solution for the sensor tube appears to be an image dissector (of the same type as used in the laboratory Oculometer) having as high a sensitivity as possible in the Oculometer operating band -e.g., with an S25 photocathode.

Recommended Components

This section describes the optical and electro-optical components that will be utilized in the Oculometer and why they were selected.

Helmet Marker

It is recommended that the helmet marker be constructed from a No. 3111 hexagonal plastic filled reflector manufactured by the Stimsonite Division of the Elastic Stop Nut Corp. of America. This reflector would have to have the cube faces gold coated to fulfill the angular tracking requirements as specified previously. The basic cubical structure of this material is well suited to provide the required signal return. The outline shape of the helmet marker could be easily cut from this material. Figure 51 is an observation angle characteristic curve for the uncoated material and demonstrates the divergence of the reflected beam of light from this material. Unfortunately, the rate of change with entrance angle and orientation angle is relatively meaningless for the uncoated reflector.

Observation Angle: The angle included by a line from the light source center to the reflector center and a line from the reflector center to the observer. It is θ in Figure 52a.

Entrance Angle: The angle included by the reflector central axis and a line from the light source to the reflector center It is ϕ in Figure 52a.

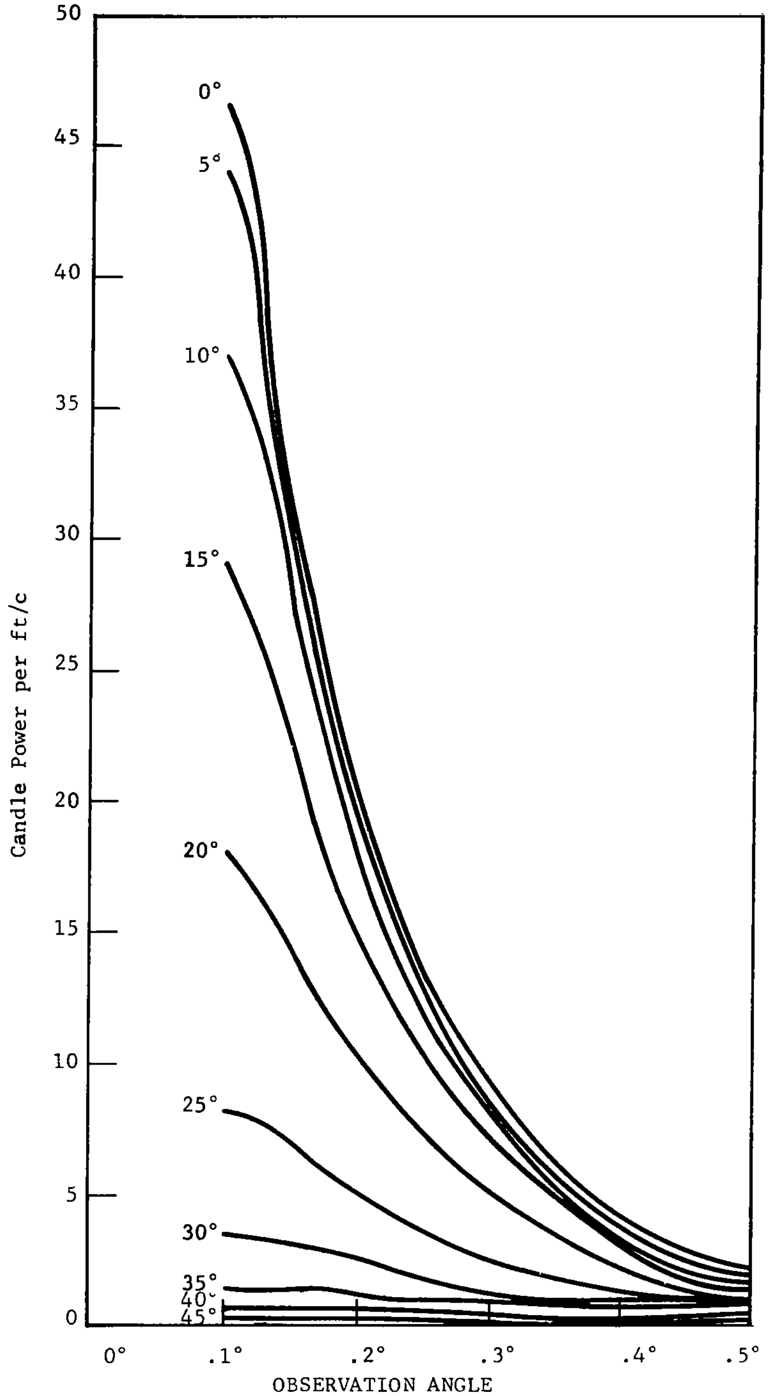


Figure 51 HELMET MARKER CHARACTERISTIC CURVE

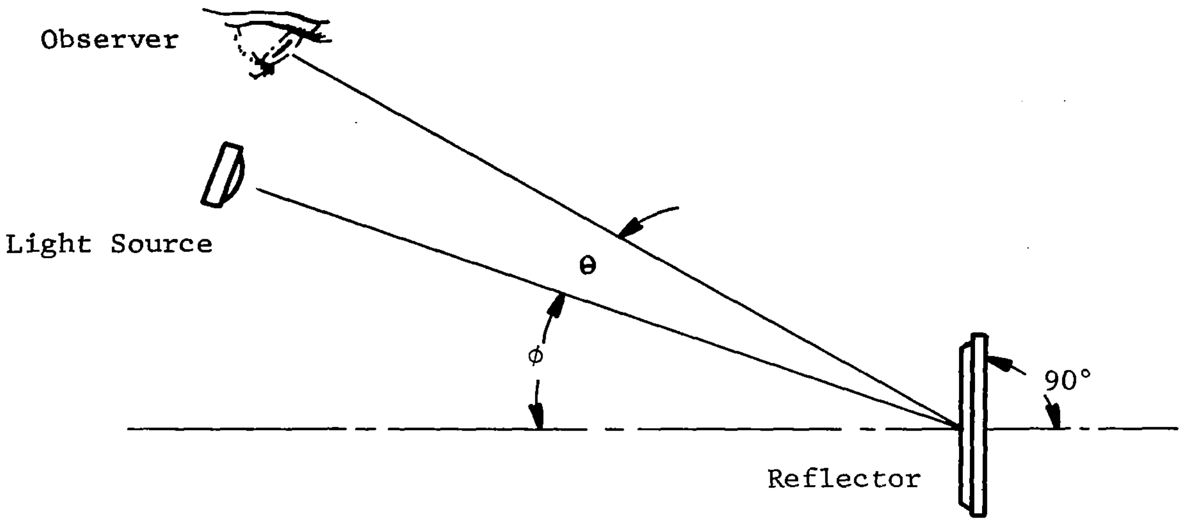


Figure 52a OBSERVATION ANGLE (θ) AND ENTRANCE ANGLE (ϕ)

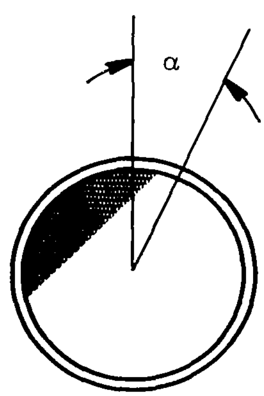


Figure 52b ORIENTATION ANGLE

Orientation Angle: The angle of rotation (from the "top-up" position) of the reflex reflector about its own axis, in a clockwise direction as viewed from the observation position. It is α in Figure 52b.

Pupil Illumination Source As discussed previously, the xenon short arc is the best pupil illumination source. It fulfills the requirements of:

(a) Illuminating all eye space without the source image on the retina exceeding the maximum safe retinal brightness.

(b) Simultaneously providing a means of discriminating against false highlights generated by the sun.

This source must be operated in such a way as to avoid undesirable bright spots in the arc that may exceed the maximum safe brightness for the retina.
There exists two possible arcs at this time which satisfy the prior requirements. They are:

A. A 150 watt xenon illuminator, model 150 x 8R manufactured by Varian Associates, Eimal Division.

B. A 75 watt standard xenon short-arc adapted to ac operation by Englehard Hanovia, Lamp Division.

The Varian unit is the first unit to apply the sealed beam principle to the xenon short arc lamp. This unit offers:

A. The maximum protection to catastrophic failure,
B. The maximum output intensity because of the built in reflector.
C. Both parabolic and elliptical reflectors.
D. Minimum package size.
E. Maximum protection against bright spots in the arc since the arc is aligned along the beam axis.

For these reasons the Varian unit is recommended as the pupil illuminator source.

Telephoto Lens The best suited telephoto lens assembly and layout appears to be the panel mounted configuration described in the Section entitled "The Optical System." The illumination optics and the collection optics are truly mounted in the cockpit instrument panel as shown in Figure 46 and 47 in that system.

Several comments about the 16 in. and 8 in. panel mounted systems are in order here. First, they were both designed so as to maximize the imaging quality for the given system size. Because the negative lens is located midway between the photocathode and the positive lens, the ray bending introduced by the negative lens is minimized and image quality is maximized. Obviously, as the system size is decreased (say from 16 in. to 8 in.) the ray bending increases and image quality goes down although focusing is easier. However, it is believed the 8-inch system will give adequate quality, and perhaps even shorter systems can be used. The ultimate practical size will have to be determined by computer ray traces and it is anticipated that both the positive and negative lenses will have to be of at least doublet construction.

SYSTEM CONFIGURATION

The Oculometer system can be designed for installation in an aircraft in at least three possible locations. These are:

A. Behind the pilot suspended from the cabin roof.
B. Under the pilot's seat
C. In the instrument panel

Regardless of which system is felt to be more desirable, the actual dimensional design must be considered a unique problem for each type of aircraft. This is noticeably apparent in the relative seating of the pilot, copilot, flight engineer, and navigator in the large transports and the contemporary fighters.

Any of the proposed Oculometer systems will require the use of a moving mirror along with the necessary drive motors and resolver readout mechanisms for control of azimuth and elevation coverage at eyespace. This mirror assembly can be located in or on the instrument panel in a circle ≈3 inches in diameter and below the horizontal axis of the viewer's eye by approximately 25 degrees.

The entire mirror assembly depth is also ≈3 in. Notice that it is not necessary to bury this entire moving mirror drive assembly in the panel as indicated in Figure 53 through 56. The location on the panel of the moving mirror is determined by several factors:

A. The availability of space on the instrument panel

B. The seating configuration of the pilot and copilot if both are to be viewed. Side by side seating necessitates a centrally located mirror for the best coverage of the pilot and copilot while front and back seating is best covered by a mirror offset to one side and thus permitting rear seat viewing over the pilot's shoulder.

C. The location of frequently used switches or levers that would interrupt the light path between the moving mirror and the basic Oculometer

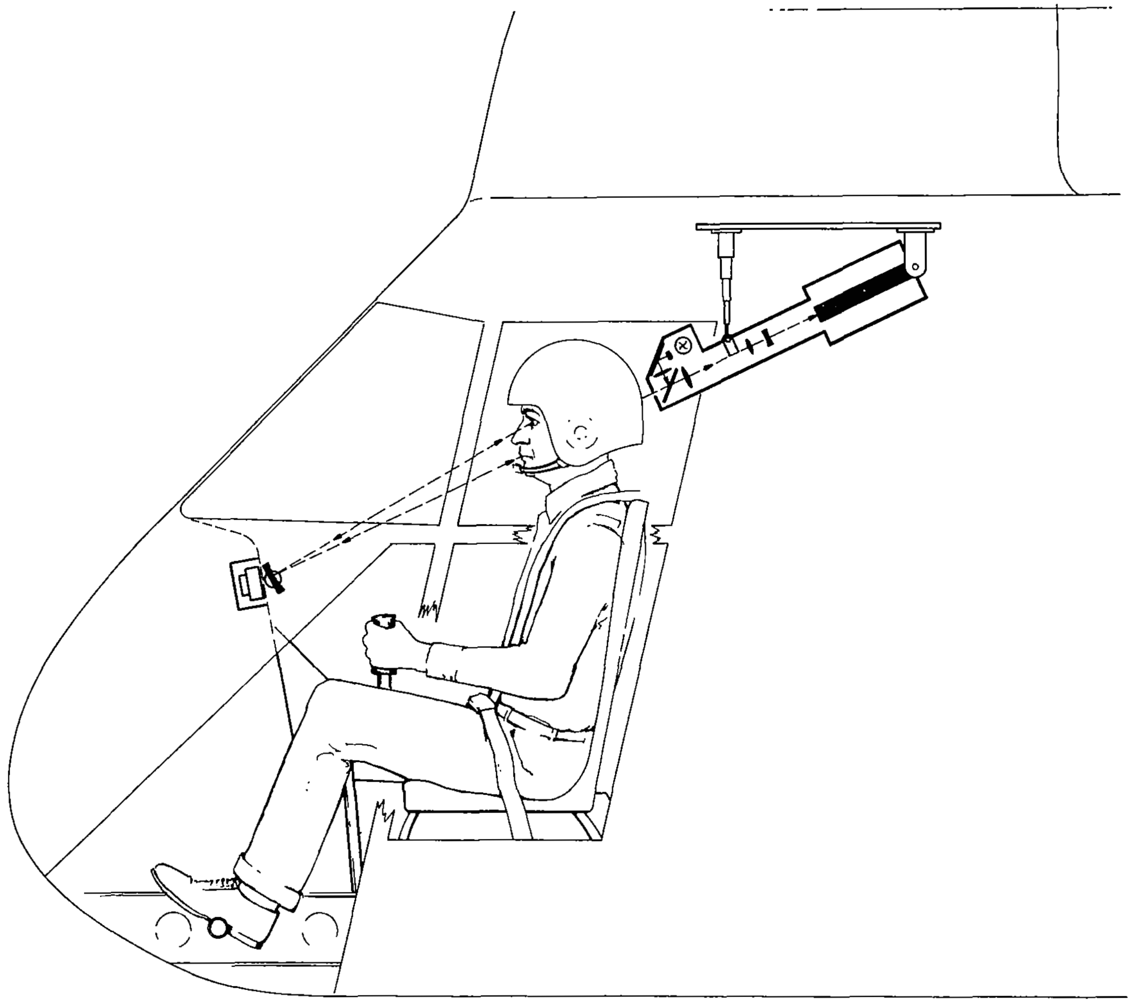


Figure 53 OCULOMETER IN BOEING CH46 HELICOPTER

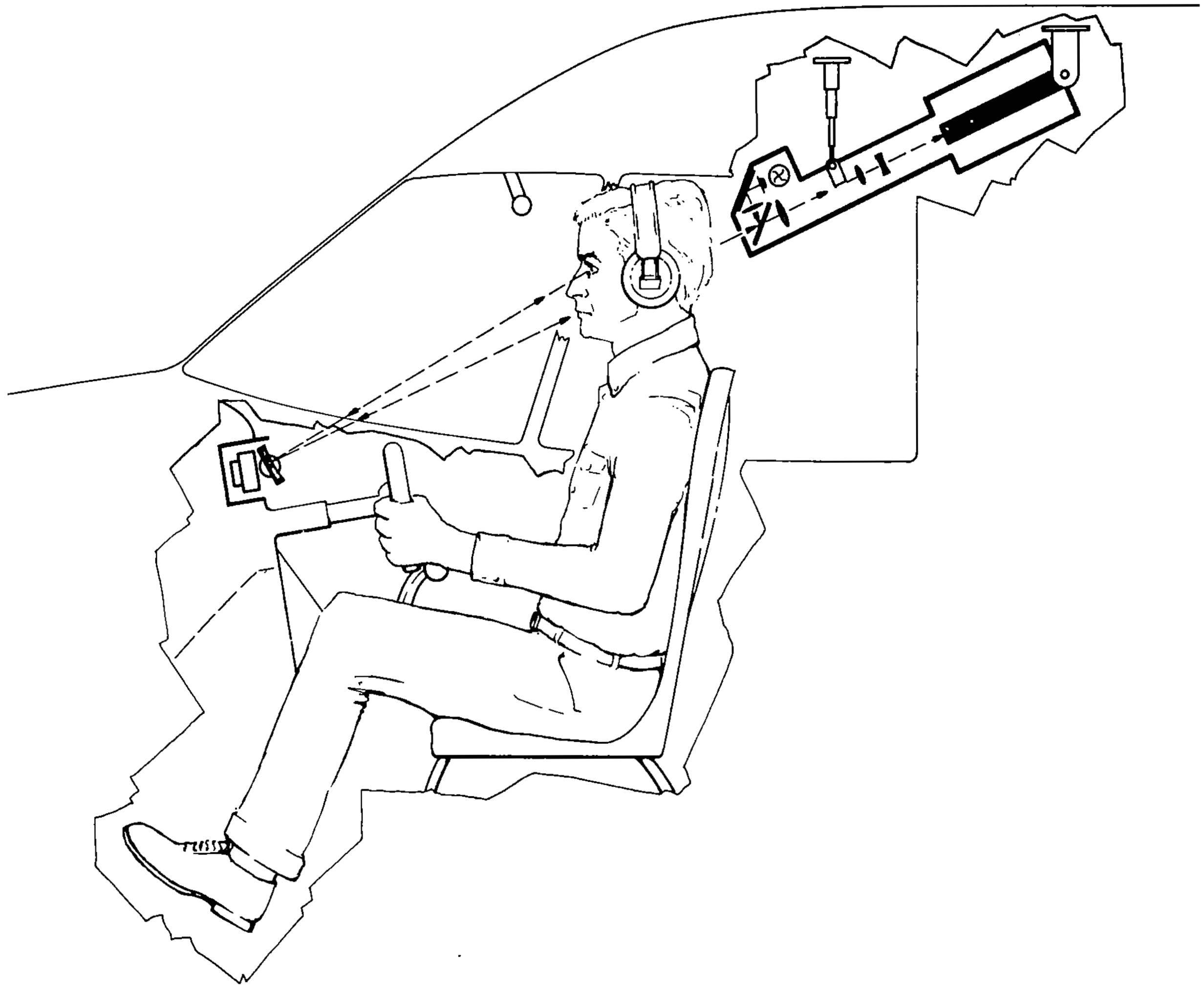


Figure 54 OCULOMETER IN LOCKHEED C141 STARLIFTER TRANSPORT

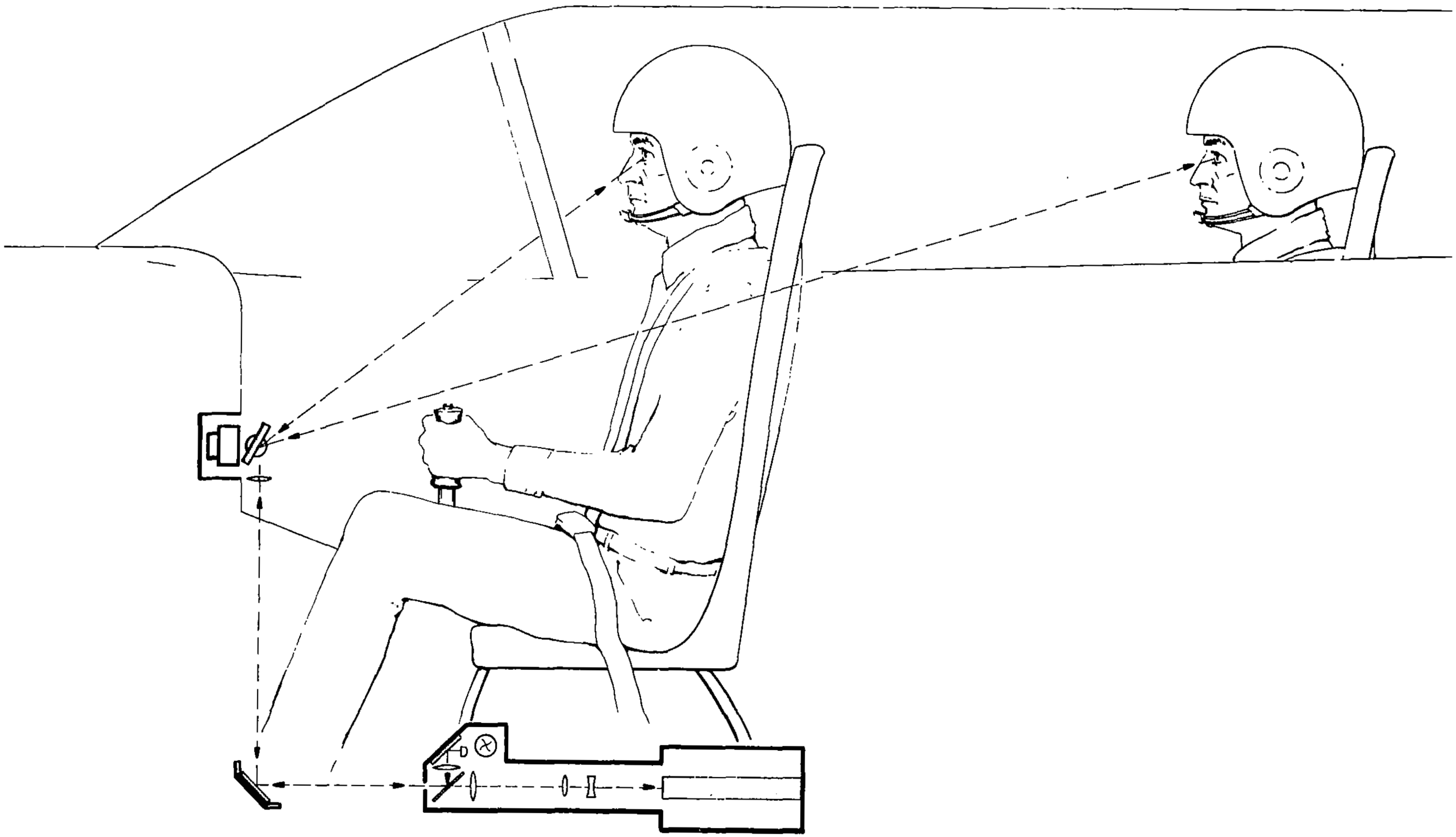
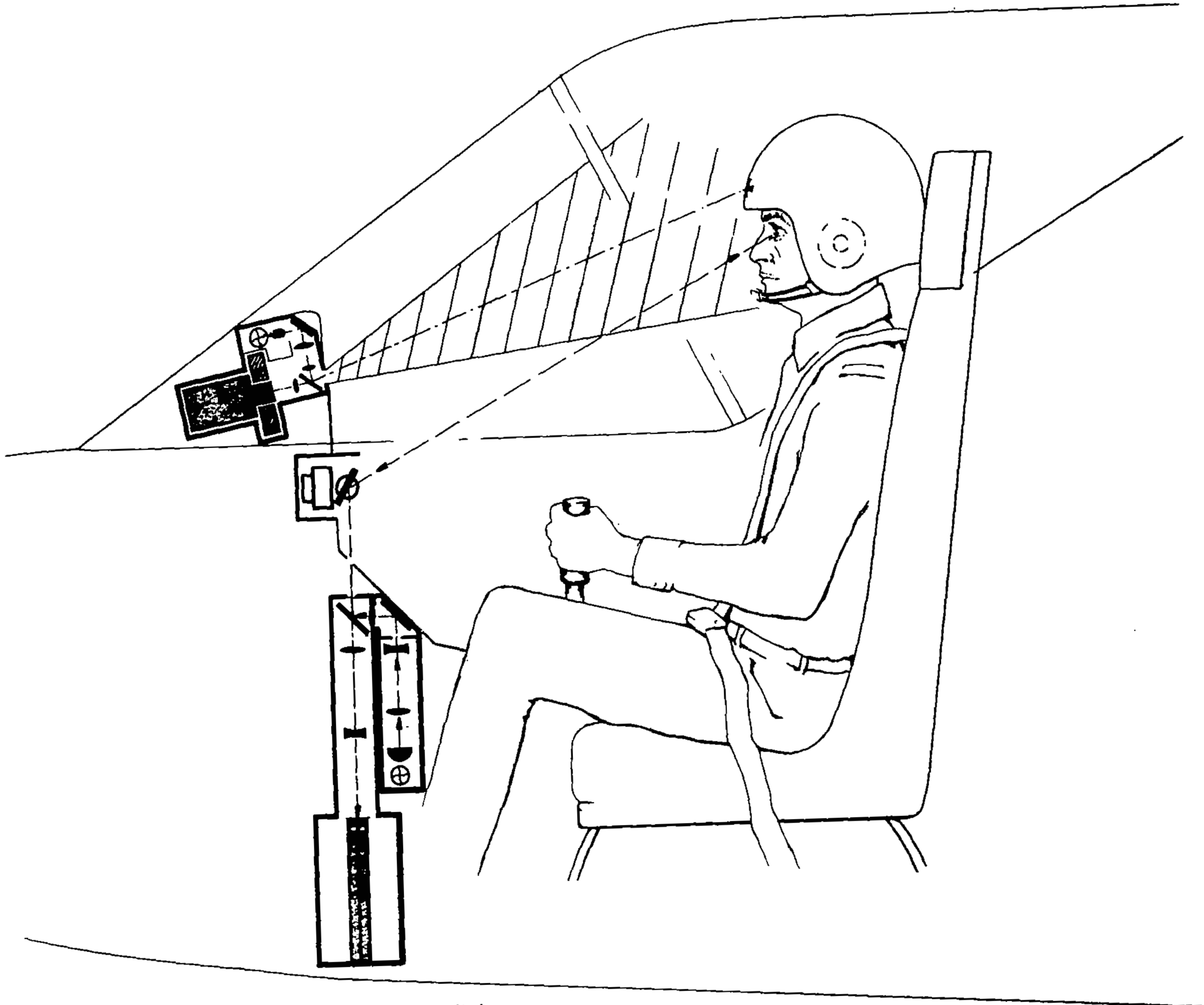


Figure 55 OCULOMETER IN LOCKHEED T-33 TRAINER



Approximate Size of Helmet Marker Acquisition and Tracking System = 37 in^3

Figure 56 OCULOMETER IN HAWKER SIDDLEY P1127 V/STOL FIGHTER

Various mounting configurations for the pupil acquisition and tracking systems are shown in Figures 53 through 56. These system layouts shown are to scale. The first of these configurations is the following:

A. Overhead Mounting

Figure 53 CH 46 Helicopter

Figure 54 C141 Starlifter Transport

The arrangement can monitor the pilot, copilot, flight engineer, or navigator by appropriately rotating the unit about the rear support pivot point. When the Oculometer is not in use, the unit can be raised by telescoping the front support, and stored against the cabin roof. The configuration utilizes a concave moving mirror. The concave mirror serves as a focusing element, since the Oculometer to pupil distance is twice that of a panel mounted configuration. The use of a focusing moving mirror (spherical surface) does not introduce appreciable distortion or aberration caused by off-axis imaging. The assets of this system are as follows:

1. The maximum mobility is provided to allow monitoring various cabin area while in flight.

2. A minimum amount of relocation is required for existing panel instrumentation.

3. A minimum danger exists to direct sun image forming on the photocathode of the image dissector since the overhead areas in the cabin are effectively masked.

The system, however, does have inherent weaknesses. These are:

1. The system is susceptible to a total blackout during the operation of certain overhead switches on the power panel of a helicopter and/or certain overhead flight control levers of a large multiengine aircraft. This blackout occurs if the pilot's or copilot's arm is interjected into the illumination path of the Oculometer.

2. Nonlinearities are generated in image magnification versus pupil to Oculometer range by the focusing moving mirror.

3. The helicopter mounting configuration must overcome any vibration of the Oculometer relative to the pupil. The large amplitude-low frequency vibration from the rotor assembly must be damped by the mounting assembly.

A configuration of this nature would be equally well suited to such aircraft as the Boeing 747, the XC 142 multiengined V/STOL and the proposed SST.

The second possible configuration involves the location of the Oculometer under the pilots seat or in the side of the fuselage and is discussed below.

B. Underseat Mounting (Figure No. 3 T-33 Trainer)

The actual optical system is basically similar to the overhead optical system, but enables the Oculometer to be installed in a bubble canopy environment. The only differences in the optical system involves in the moving mirror. The actual mirror in this configuration is a plain mirror and an associated lens is used to achieve the function of imaging eyespace in the vicinity of the Oculometer housing. This technique is necessary to avoid rays impinging on a focusing reflector at large angles of incidence and thus creating image distortion. The penalty paid for the use of a lens is the increase in background intensity at the photocathode of the image dissector due to reflections from the curved surface of the lens. The actual Oculometer, if mounted under the seat, must be low enough to permit at least 12 inches of vertical seat motion. Front and back seat monitoring is permitted with this configuration by injecting the illumination beam into eye space either over the pilot's head in an aircraft such as the Bell Huey

Cobra or the proposed AAFSS Helicopter, or by offsetting the system to the side of the fuselage and using the moving mirror to inject the illumination beam past the pilot's shoulder in the case of Figure 54, a Lockheed T-33 jet trainer. This system would utilize less instrument space than a panel mounted system and would also provide easier access for modification or repair than a panel mounted system. However, being fixed in installation it can monitor only the pilot or the copilot.

C. Panel Mounted System

The final configuration is demonstrated in Figure No. 56. The illustrated example is that of a Hawker Siddeley P1127 contemporary V/STOL Fighter. A configuration of this type would also be usable in an aircraft such as the A-7 crusader.

This particular configuration shows an optional all-electronic head marker acquisition and tracking system. This particular sub-system covers the entire eye space region instantaneously and independently of the moving mirror. It can be used in applications where very high speed acquisition and reacquisition are of prime importance. In this case the moving mirror is not used for search but is merely commanded to point at the eye, once the position of the head marker has been determined by the marker system.

This configuration is the most compact, since the illumination and collection path is half the length of the other configurations. Thus, simpler, lower loss, collection optics are permitted for imaging eye space onto the photocathode of the image dissector.

The less complicated collection optics lends itself more readily to image minification techniques if a further reduction in the size of the collection optics is necessary.

This system can monitor the pilot and the copilot whether side by side seating or front to back seating is employed. This task is similarly accomplished by appropriately offsetting the moving mirror.

The concept that the instrument panel must be modified to accept the Oculometer does have one advantage. That advantage is the internal location of the unit establishes the minimum likelihood to accidental damage in rough air turbulence or in combat maneuvers.

SUMMARY

The basic remote Oculometer system, outlined in the Introduction, has been analyzed in detail in the main body of this report. The results of this work will be summarized here in the form of (1) Performance Summary, (2) a review of the primary technical considerations involved in each part of the system, (together with specific design recommendations where appropriate: in some cases experimental work is recommended to establish design details.) and (3) a design summary.

Performance Summary

Based upon the results of this study the following performance should be realizable:

Angular Range: about ±25 degree vertically, ±35 degrees horizontally (regular Oculometer); ±40 degrees vertically ±60 degrees horizontally (eccentric pupil technique). (See Figure 7)

Noise Level: ≈ 0.1 degree (regular Oculometer)
≈ 2 degrees (eccentric technique)
≈ 0.5 degree (with panel markers)

Other Errors: Head Roll, ϕ. ($\phi/10$ monocular system: $\phi/50$ binocular system with averaging.)
Pupil Diameter Changes not yet established.
Corneal/Pupil interference .2 degree
Ambient illumination effects ≈ .2 degree

Acquisition Time: Head Marker ≈ 0.1 s
Eye (after marker acquisition) ≈ 0.1 s

Reference should be made to the relevant sections of this report for more exact discussion of the performance figures.

Technical Review

<u>Illumination System</u> A xenon short arc illuminator is recommended because it provides

(1) the best possible sun discrimination capability

(2) an adequate, safe, illumination intensity.

It is important that the portion of the arc, utilized as the effective illumination source in the Oculometer, have a fairly uniform intensity, and that the peak intensity of this region be accurately determined for all operating conditions. The design of the illumination optical system must be such that the retinal safety criterion (as discussed in this report) be observed for the maximum radiance of any small segment of the effective Oculometer source. Particular attention must be paid to achieving very high reliability in this aspect of the design. For example, consideration should be given to the incorporation of an automatic lamp cutoff circuit activated by an internal radiation sensor monitoring the eye illuminating radiation.

The maximum source radiance - as seen by the eye - will be limited to 15 $watts/cm^2/steradian$. The spectral radiance of the xenon arc at $.825\mu$ is about 4 $kW/cm^2/steradian/micron$. The spectral bandwidth of the system should, therefore, be $.02\mu$ and the lamp-eye transmission factor (including the beam splitter) should then be 0.2. In the marker search mode, however, the lamp intensity should be reduced (by reducing the electrical input) by a factor of 10 times (e.g. For reasons of eye safety, and photocathode safety). The intensity of the lamp should not be increased, above this value, until the pupil has been acquired and has been tracked for about 50 ms. Then the lamp intensity should be controlled (between the specified minimum and maximum values) in order to yield a pupil signal of constant intensity. Thus for small pupils the lamp intensity would be relatively high, and for large pupils relatively small.

It is to be noted that even if - due to a small malfunction - the eye were to be illuminated at the specified maximum intensity when the pupil diameter was large (e.g., 7mm) the retinal safety criterion would not be violated. However, the margin of safety would, of course, then be 10 times less than that existing in the properly operating system. The control of lamp intensity (according to the received pupil signal level), is recommended, therefore, as an additional safety factor designed to reduce the probability of a retinal accident to an infinitesimally small value.

According to the analysis presented earlier, the use of the xenon source should provide an effective sun (ambient) discrimination capability under nearly all conditions. Additional discrimination could be obtained by modulating the xenon source. It is recommended that the sun discrimination performance of an unmodulated system be evaluated first. It can then be converted easily to a modulated system, if this proves to be desirable.

Attention is directed to the question of Oculometer source visibility, relative to the ambient illumination. As shown in Table I a considerable price is paid, in terms of received signal level, if it is specified that the illumination source be completely invisible. It is recommended that a subjective source luminance in the range from the ambient luminance be accepted.

It is recommended that specific experimental verification of the "bright pupil" analysis presented in this report be performed to establish the optimum F/number for the Oculometer optical system.

Sensor Tube As discussed elsewhere, it has been determined that an image dissector is the best sensing tube for the Oculometer. A very important design choice is the diameter of the scanning aperture in this tube. It should be as small as possible to give high resolution and good accuracy. However, various practical factors, such as:

- electronic focusing of the image dissector tube
- instantaneous depth of focus of the optical system
- degree of circularity of the pupil
- electronic signal level
- linear tracking range
- acquisition time

etc.

set a limit to the minimum aperture diameter: a diameter value of .005 in. (at the eye) is recommended.

It is important to derive the maximum possible sensitivity from the sensing tube: for this reason an S25 (or an extended red S20) photocathode should be used.

Acquisition System As a compromise between performance and system complexity, it is recommended that a head marker (of corner reflecting material) be used for initial acquisition. Once the marker is acquired (using the moving mirror in a raster search mode) the position of the eye will be known to within a small tolerance. Electronic search for the eye can then be performed within this small tolerance region. An acquisition time of about 0.2 seconds can be achieved in this manner. Factors requiring particular attention are:

(a) moving mirror: minimize inertia and maximize torque to derive maximum possible search rates.

(b) eye acquisition electronics: derive optimum detection criterion so that reliable detection can be based upon the collection of a minimum number of photoelectrons from the pupil.

Electronics The main electronics system should be very similar to that utilized in the mental alertness Oculometer. Specific changes recommended are:

(1) double integration in the tracking loops to give improved dynamic response

(2) optimized acquisition and loss criteria.

(3) to the maximum extent possible the electronics system functions should be performed by a digital computer (at least in developmental models).

Calibration/Data Reduction The Oculometer system must be calibrated for each individual in respect to

(a) zero offset

(b) scale factor

The exact calculation of eye direction from the raw Oculometer data involves significant computation. It is recommended that consideration be given to the degree of computation actually required, and whether this should, or should not, be performed in real time.

To augment, or replace, the direct computation of eye direction, panel markers can be used to display, graphically in real time, the subject's fixation point. (See Figure 11).

Design Summary

The following are the recommended major design choices with the reasons for them:

Sensor

Image dissector	The only tube having higher sensitivity (in this application) - the Image Dissecticon must be rejected for practical reasons.

photocathode size	1.0 - 1.5 in.	larger size unnecessary, smaller not available
photocathode type	S25	for maximum sensitivity at Oculometer band.
aperture size	0.005 in.	Small enough for good accuracy yet large enough for practical optical focusing.

<u>Electronics System</u> The general system will be the same as in the laboratory Oculometer. Consideration should be given however, to the desirability of implementing this system by digital techniques - for example with a small general purpose digital computer and D-A and A-D converters. The potential advantages are reduced cost, flexibility of design, and improved performance.

<u>Illumination</u> 75W xenon short arc for good ambient discrimination

Operating Band	Typically 0.825 $\mu \pm 0.01 \mu$
Intensity at the eye	1.5 watts/cm^2/steradian (for a large pupil) 15 watts/cm^2/steradian max (for a small pupil)

Eye Space

Instantaneous:	1 in. x 1 in.	A larger eye space would require higher lamp power, and better resolution in the image dissector, also may result in excessive background illumination due to scattering within the system. A smaller eyespace would not be able to contain the eye image under all conditions.
TOTAL	12 in. x 12 in. x 12 in.	Design choice-can be larger
F/number	50-100	Must be high enough to ensure good pupil/iris contrast under all conditions
Focusing System	3 ft - 5 ft of eye Oculometer range	
Method		Small axial motion of negative lens of a telephoto lens combination.

Focus Sensor	Focusing lens made to execute slight "dither" (in and out of focus) Tracking video analyzed to derive a modulated signal proportional to focus error (may require a tracking dither).
Moving Mirror System	Single mirror gimbal mounted torque motor drive (1 oz-in. and 20 oz-in.) Rotary Variable Differential Transformer pick-off.

APPENDIX A
BASIC OCULOMETER SENSING PRINCIPLE

The basic sensing principle of the Oculometer is that eye direction is defined by the position of a corneal reflection (of the radiation source within the Oculometer), relative to the center of the pupil.

(imaginary) point at the center of the pupil, that will be collected, is the ray parallel to the incident collimated bundle. The displacement of the corneal reflection from the center of the pupil is, therefore, (from Figure A.1) K sin θ where θ is the angle between the geometric axis of the eye and the direction of the incident collimated beam (which is a reference direction, the optical axis of the Oculometer) and K is a dimensional constant of the eye. Thus by measuring the displacement of the corneal reflection from the center of the pupil, in the eye image, a measure is obtained of the direction of the geometric axis of the eye.

Under the conditions stated, the displacement between the rays from the center of the pupil and from the corneal reflection is independent of the position of the eye in all three dimensions. That is, if the eye moves (with no rotation) in any direction, the displacement between the two rays is invariant. The displacement between the rays is solely a function of the angular direction of the eye.

APPENDIX B
DESCRIPTION OF LABORATORY OCULOMETER

The Oculometer is an electro-optical device that dynamically records the pointing direction of the human eye and certain other eye responses. It is not attached to the subject, and it operates with essentially invisible infrared radiation.

The laboratory Oculometer consists of an optomechanical unit (see Figure 3) and an electronics unit.

In operation, the eye is placed near a dichroic beam splitter at one end of the optomechanical unit. The eye is then illuminated by IR radiation from a source within the unit. An image of the eye is formed at the photocathode of an image dissector tube, also contained within the optomechanical unit. The electronics unit processes the video signal from the image dissector and generates scan signals for the image dissector, causing it 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 system also provides a measure of pupil diameter, pupil position, and blink occurrence.

BASIC SENSING PRINCIPLE

The basic sensing principle of the Oculometer is that eye direction is defined by the position of the corneal reflection of the radiation source within the Oculometer, relative to the center of the pupil. (See Appendix A)

OPTOMECHANICAL UNIT

The optomechanical unit utilizes a novel illumination technique in which the eye is irradiated with almost invisible IR radiation to show the pupil as a bright uniform disc, together with a small corneal reflection, against a virtually black background.

The new illumination technique is illustrated in principle in Figure B.1. Light is projected from a small light source onto the retina via a beam splitter in front of the eye. An image of the light source is formed on the retina, and a fraction of the incident radiation is scattered back from this area of the retina. Some of the scattered rays are collected by the eye lens and then refracted in such a way that when emerging from the eye, the rays retrace, exactly, the path of the incident rays from the light source. The emergent rays are passed through the beam splitter to a lens, which is located at the virtual image of the light source in the beam splitter. Since the emergent rays are focused back, by the eye lens, to the light source, the emergent rays passing through the beam splitter converge to a small area at the lens, corresponding to the small area of the light source. The power of the lens is chosen to cause an image of the pupil to be focused onto the screen, which in the Oculometer is the photocathode of an image dissector.

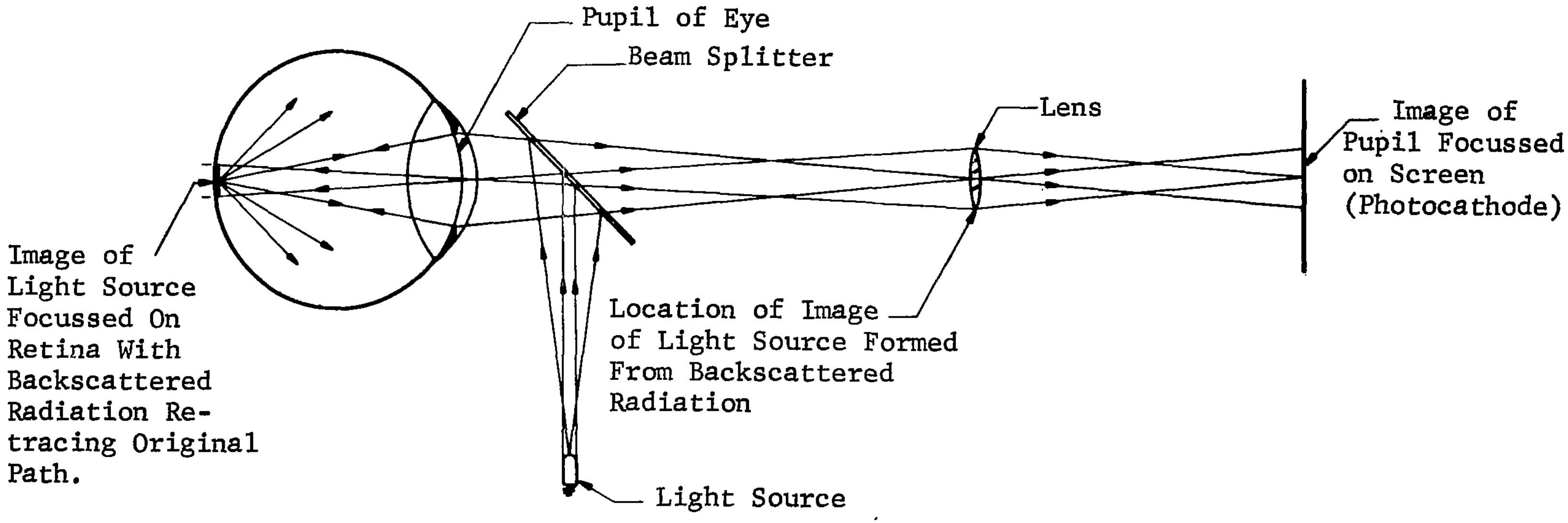


Figure B.1 RETINAL METHOD OF PUPIL/IRIS BOUNDARY ILLUMINATION

A prime advantage of this illumination method is that the F/number of the collecting optics, i.e., the aperture of the lens in Figure B.1.does not govern, in a conventional way, the brightness of the pupil image on the screen. The dominant factor in this respect is the F/number of the eye lens. This fact makes possible the use of a high F/number optical system which yields, in turn, the following advantages:

(1) good depth of focus, and
(2) improved resolution.

Moreover, with a high F/number optical system, all other regions of the eye, even though they are illuminated by the same light source, do not show up brightly on the screen (Figure B2). The pupil area stands out clearly thereby facilitating acquisition and reliable tracking.

An optical schematic of the Oculometer is shown in Figure B3 Radiation from a tungsten filament lamp is collected by an F/1.5 double plano convex lens system and an enlarged image of the filament is formed at the illumination aperture. The illumination aperture itself is at the focal plane of the main illumination lens and appears, to the eye, therefore, to be at infinity.

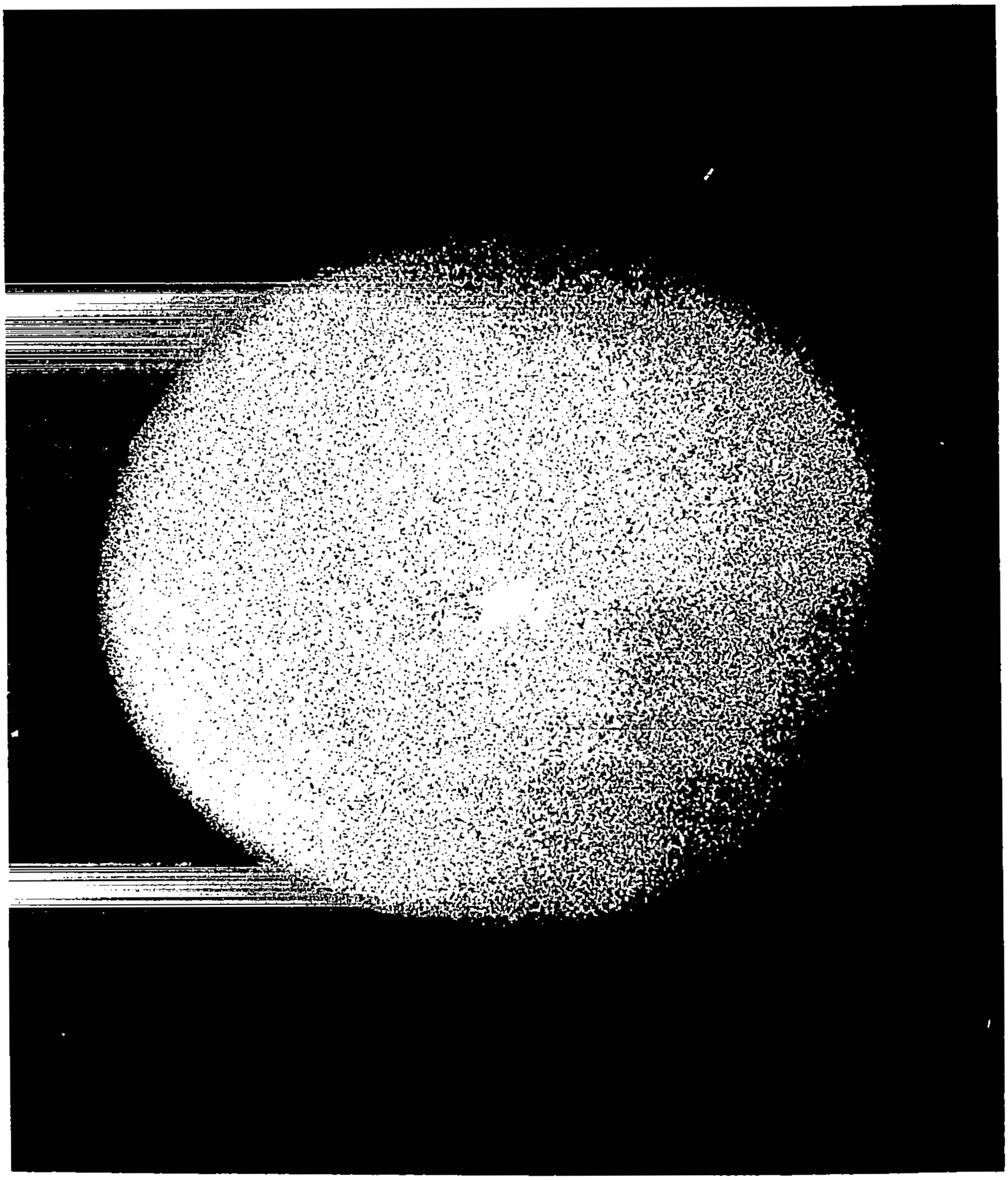


Figure B.2 PHOTOGRAPH TAKEN AT THE IMAGE DISSECTOR PHOTOCATHODE

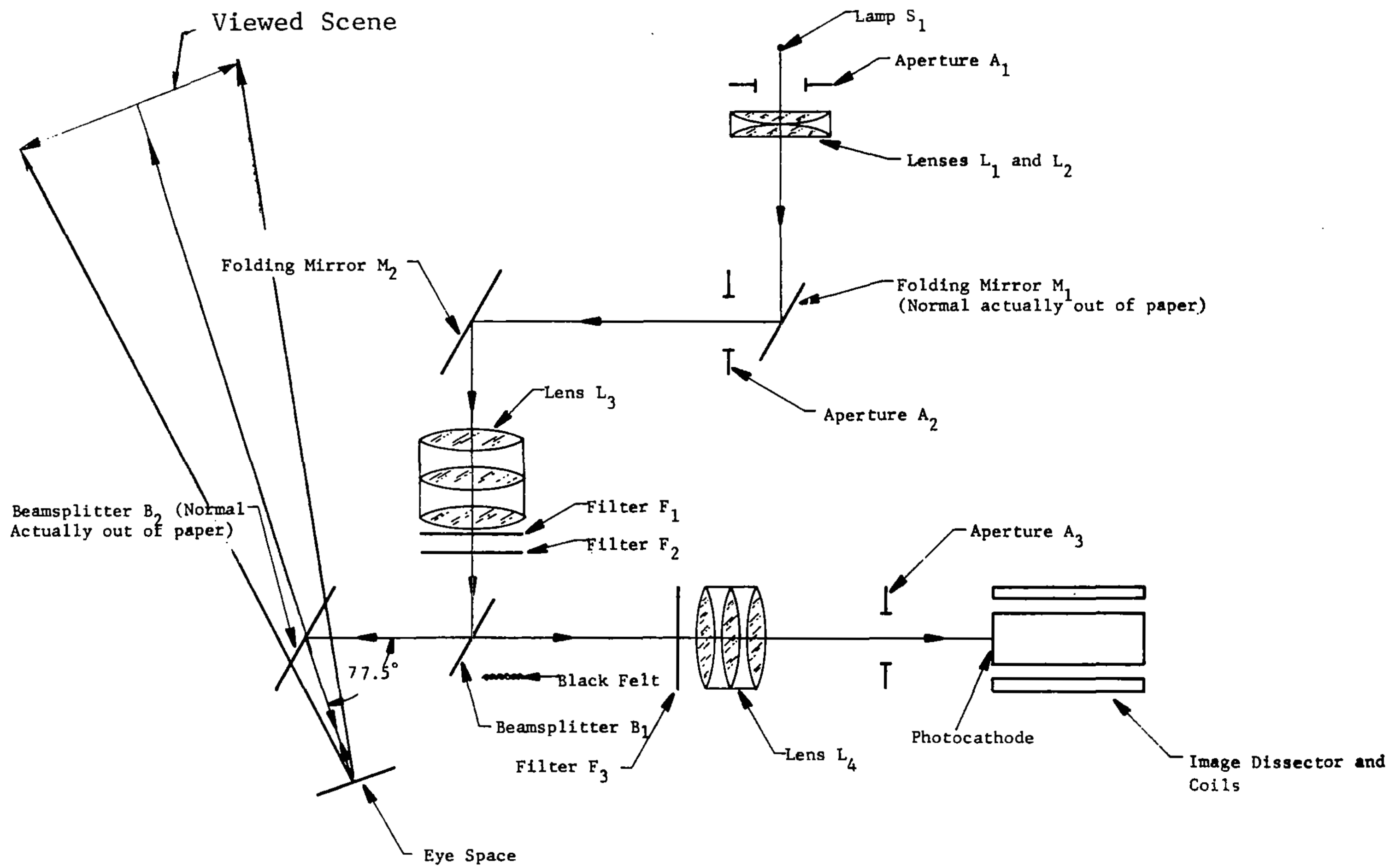


Figure B.3 OCULOMETER OPTICAL SYSTEM

The illumination rays are directed onto the eye by reflection at the neutral and dichroic beam splitters. The eye is imaged onto the photocathode of the image dissector by rays reflected from the dichroic beam splitter and transmitted by the collection aperture which is at the focal plane of the imaging lens.

The image dissector used in the Oculometer is an ITT F4011 1 1/2 in. vidissector with an S1 photocathode.

Electrons are emitted from the photocathode of this tube in proportion to the incident IR radiation. These electrons are accelerated by an electric field towards an aperture plate having a central 0.017 in. diameter circular aperture. The electrons are magnetically focused onto this plate to form an electron image of the eye.

The electron image at the aperture plate can be deflected in two dimensions by magnetic fields supplied by deflection coils. In this way any part of the electron image can be laid over the circular aperture. The electrons falling onto this clear aperture pass through to the multiplier section of the tube which has a gain of about 3×10^6. The output current from the image dissector is thus proportional to the average intensity of that region of the optical image at the photocathode corresponding to the circular aperture. The position of this region in turn, is determined by the currents flowing in the x and y axis deflection coils.

ELECTRONICS UNIT

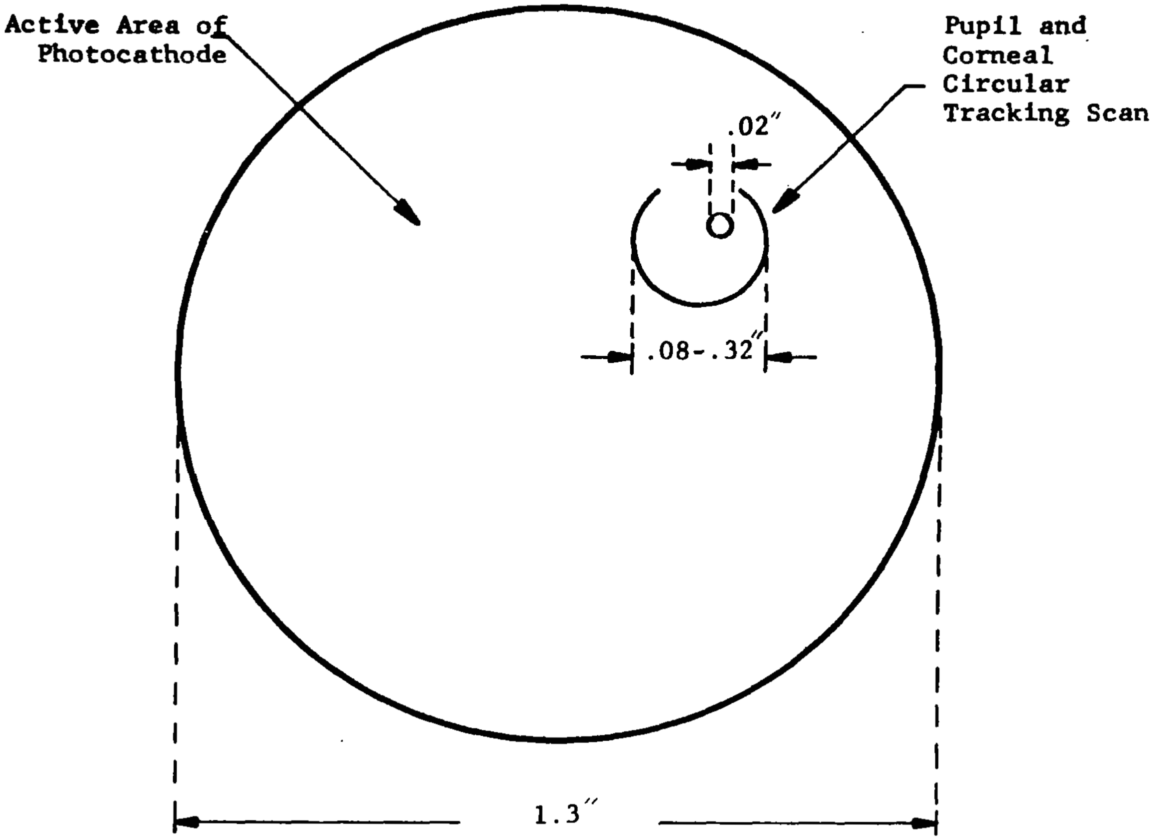
The electronics system of the Oculometer can be in any one of three states. That is,

in Pupil Track/Corneal Track,
in Pupil Track/Corneal Search,
in Pupil Search

The particular state that the Oculometer is in is determined by the corneal and pupil state sensors, based upon the signal output from the image dissector.

In the pupil track/corneal track mode the deflection coils apply a constant circular scan pattern together with pupil position and corneal position signals. The total effect is as illustrated in Figure B.4. The top portion of the circular scan is not used for pupil tracking in order to avoid errors due to obscuration of the pupil by the upper eyelid and lashes.

The image dissector output signal is processed initially to generate video signals for each of the five tracking loops, that is, pupil diameter, pupil position x and y, and corneal position x and y. The image dissector scan signals are assembled from a fixed circular scan pattern together with the computed scan position signals.



(All dimensions are in inches and are referred to the Eye Space)

Figure B.4 PUPIL AND CORNEAL TRACKING SCANS

A very simplified block schematic diagram of the Oculometer tracking system is shown in Figure B.5.

The pupil and corneal circular tracking scans are derived from a 1 kHz sinusoidal source, which in turn is derived from a master clock system. The video output from the image dissector is applied to pupil diameter, pupil position, and corneal position demodulators. The output from these demodulators is a signal proportional to the instantaneous scan position error, and is applied to the associated integrators. The integrator outputs control pupil scan diameter, pupil scan position and corneal scan position (relative to the center of the pupil). The various position and scan signals are assembled and applied to the image dissector deflection coils.

Let it be assumed that the scan system is exactly aligned with the appropriate eye detail. The output from all the demodulators will be zero and the integrator outputs will not change. If the eye displaces, then the video output from the image dissector will change. The demodulators will generate, from this video, an appropriate error signal proportional to the existing scan position error. This error signal will cause the associated integrator outputs to change in such a way as to correct the existing error in scan position. When the error has been corrected, all the error signals from the demodulators will

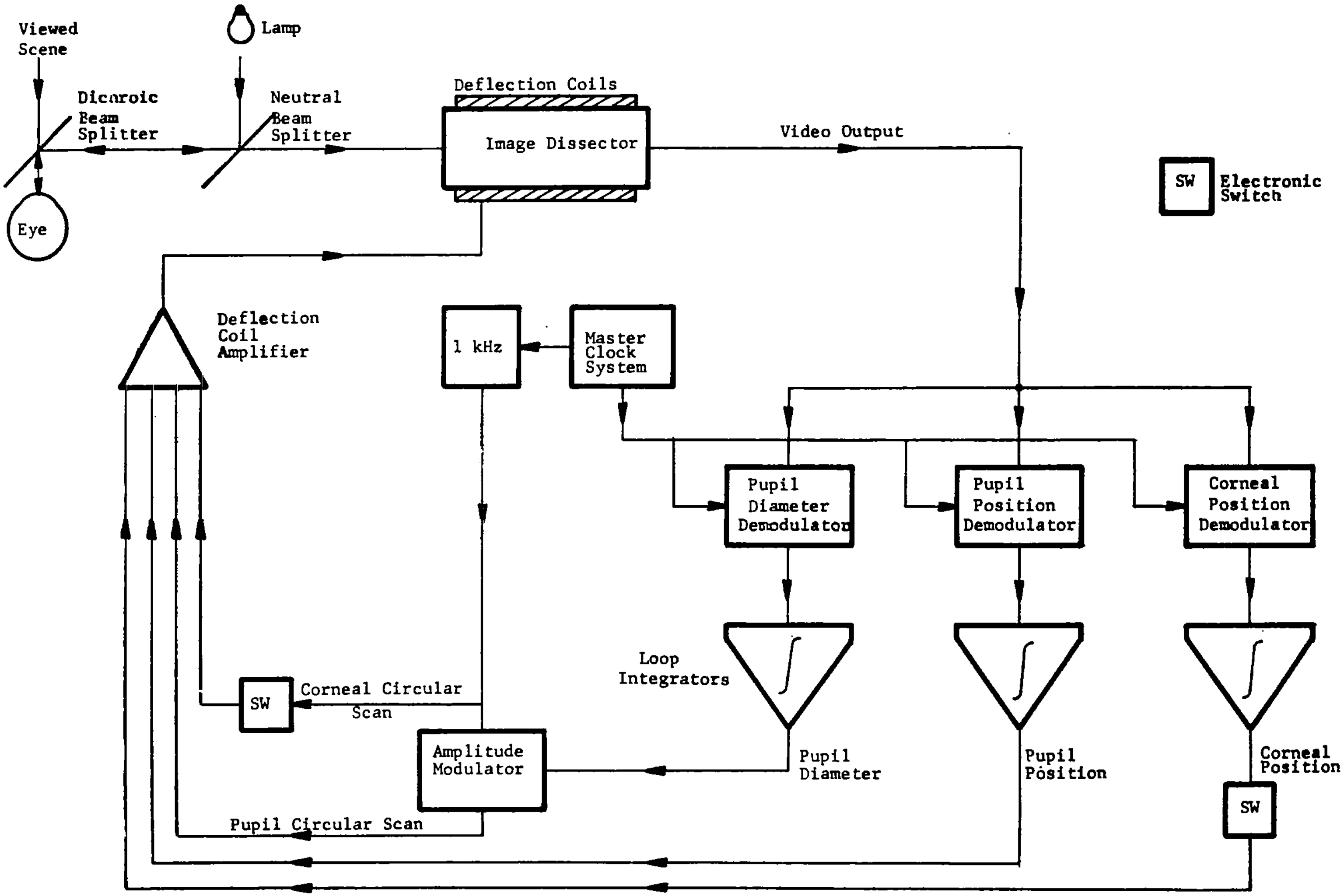


Figure B.5 OCULOMETER TRACKING SYSTEM

be zero, the integrator outputs will not change, and the scan will remain correctly positioned over the eye detail.

The basic scan period of the Oculometer is 2 milliseconds. That is, the scan pattern shown in Figure B.4 has a period of 2 milliseconds.

The video from the image dissector is processed to yield pupil and corneal scan position error signals. As illustrated in Figure B.6 this is accomplished by (effectively) multiplying the video with appropriate demodulation functions which are synchronized with the scan pattern. The pupil and corneal tracking scans are shown, in the upper part of Figure B.6, slightly misaligned from the pupil and corneal reflection. Because of this misalignment, the image dissector signal output will fluctuate as the scanning aperture of the image dissector is made, by the circular scan, to fall over alternately lighter and darker positions of the image. The resulting video signal is illustrated schematically as the first function shown in Figure B.6. The corneal and pupil x and y demodulation functions are shown next. In the Oculometer the video is multiplied by these functions to yield scan position error signals. The x demodulated video is illustrated at the bottom of Figure 13. It can be seen that if the scan is perfectly aligned with the pupil and corneal reflection there will be no 1 kHz modulation superimposed on the video and the average value of each of the

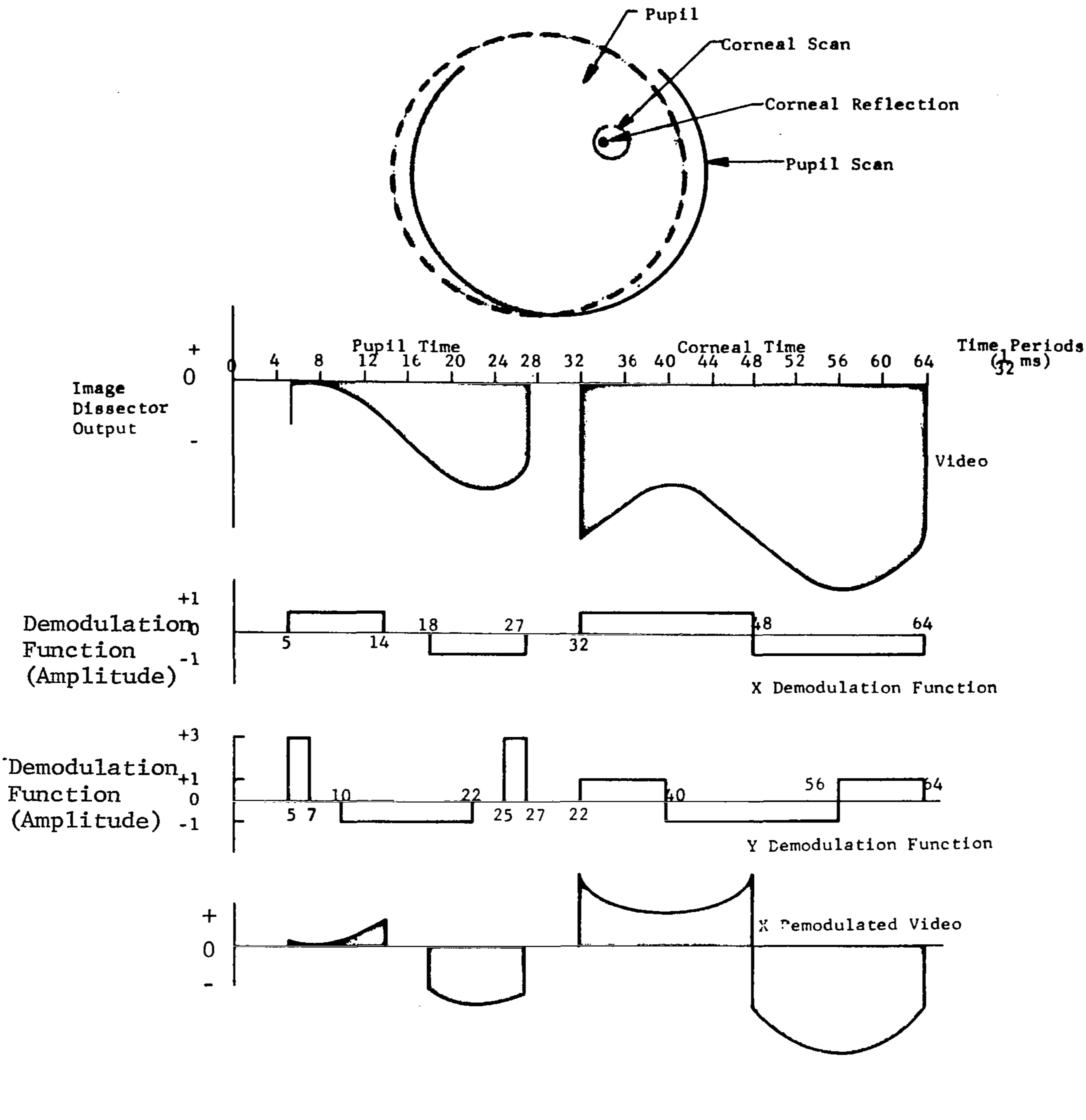


Figure B.6 POSITION DEMODULATION FUNCTIONS components; that is, pupil x and y, and corneal x and y of the demodulated video will then be zero.

In the search modes the circular scans are suppressed and the associated tracking loops are disabled. A coarse raster scan is substituted for the circular scan.

In the pupil search mode, the video from the image dissector is applied to the pupil state sensor. When the video level exceeds a threshold level determined by the setting of the pupil acquisition threshold control, the logic state of the acquisition comparator changes and the system is then held in the pupil track mode for 0.1 second. While in the pupil track mode, the video is applied to the loss of pupil track comparator. When the video level falls below a threshold level as determined by the pupil loss threshold control the pupil loss comparator changes its logic state and, if the system has been in pupil track for more than 0.1 s, causes the system to go out of pupil track.

When the system is in pupil track, the corneal time may be devoted to either corneal search or to corneal track. The corneal state is determined by corneal state sensor in a way similar to the operation of the pupil state sensor.

Eye direction is proportional to the output of the corneal integrators. These integrator outputs are applied, via electronic switches, to output amplifiers which have provision for front panel individual adjustment of gain and offset.

APPENDIX C

OCULOMETER ACCURACY AND EYE CHARACTERISTICS: ANGLE LAMBDA

1. The angle lambda is the angle between the foveal axis and the optical axis of the eye. The average value of this angle is 5 degrees (Ref 3) (The foveal axis is displaced in visual space from the optical axis in the nasal direction).

2. The Oculometer determines the direction of the optical axis. Provided that there is no unknown rotation of the eye about the optical axis, a determination of the direction of the optical axis defines the direction of the foveal axis. However, errors will be introduced whenever there is unknown rotation of the eye about the optical axis.

Let ψ be the angle of rotation about the optical axis. The corresponding error in the determination of the direction of the foveal axis is:

$$\delta = \frac{5 \pi \psi}{180} = 8.83 \times 10^{-2} \psi \qquad (1)$$

3. When the axis of the eye is deflected from the zero (straight ahead) position to some other position, the eyeball moves (nominally) according to Listings Law (Ref 4). This states that any displacement from the zero position is equivalent to a single rotation about an axis in the equatorial plane. (The equatorial plane is a plane in the socket, corresponding to the equatorial plane of the eye in the zero position).

Rotation of the eye about theoretical axis may arise as follows:

(a) Rotation of the head about the optical axis of the eye.
(b) Deviations from Listings Law.
(c) Rotation of the head about any axis perpendicular to the optical axis of the eye.

These effects are considered in detail below:

3.1 Let the head rotate through an angle α about the optical axis. The ψ is equation (1), is given by

$$\psi = \alpha$$

3.2 According to Ref 5 when there is zero convergence of the two eyes, deviations from the Listings Law are small (e.g., 1/4 degree) for eye rotations of the magnitude incurred in normal vision. For eye rotations of 30 degrees, a 1 degree deviation is reported, and for very large eye rotations the deviation is 3 degrees to 5 degrees.

When the eyes are converging on an object at 30 inches the convergence is about 5 degrees and a deviation of approximately 1 degree may then occur from Listings Law due to convergence.

3.3 Let the eye rotate from the zero position (A) to position (B) (Figure C.1). Now let the head suffer a pure rotation (about one axis) to bring it to position C.

Let OX, OY be rectangular axis fixed in the plane of the pupil of the eye in position A. Let OX^1, OY^1 be the displaced axes at position B. Let θ_1 be the angle between the axis OX and the great circle path AB at A (Figure C.1a). Then, by the nature of the eye rotation (Listings Law), the axes OX', OY' will make the same angle with the great circle BD at B (Figure C.1b) as at A (Figure C.1a). Similarly let θ_2 be the angle, at B, between OX' and to great circle path BC. Then θ_2 is also the angle between OX" and the great circle BD at C. (Head rotation between B and C).

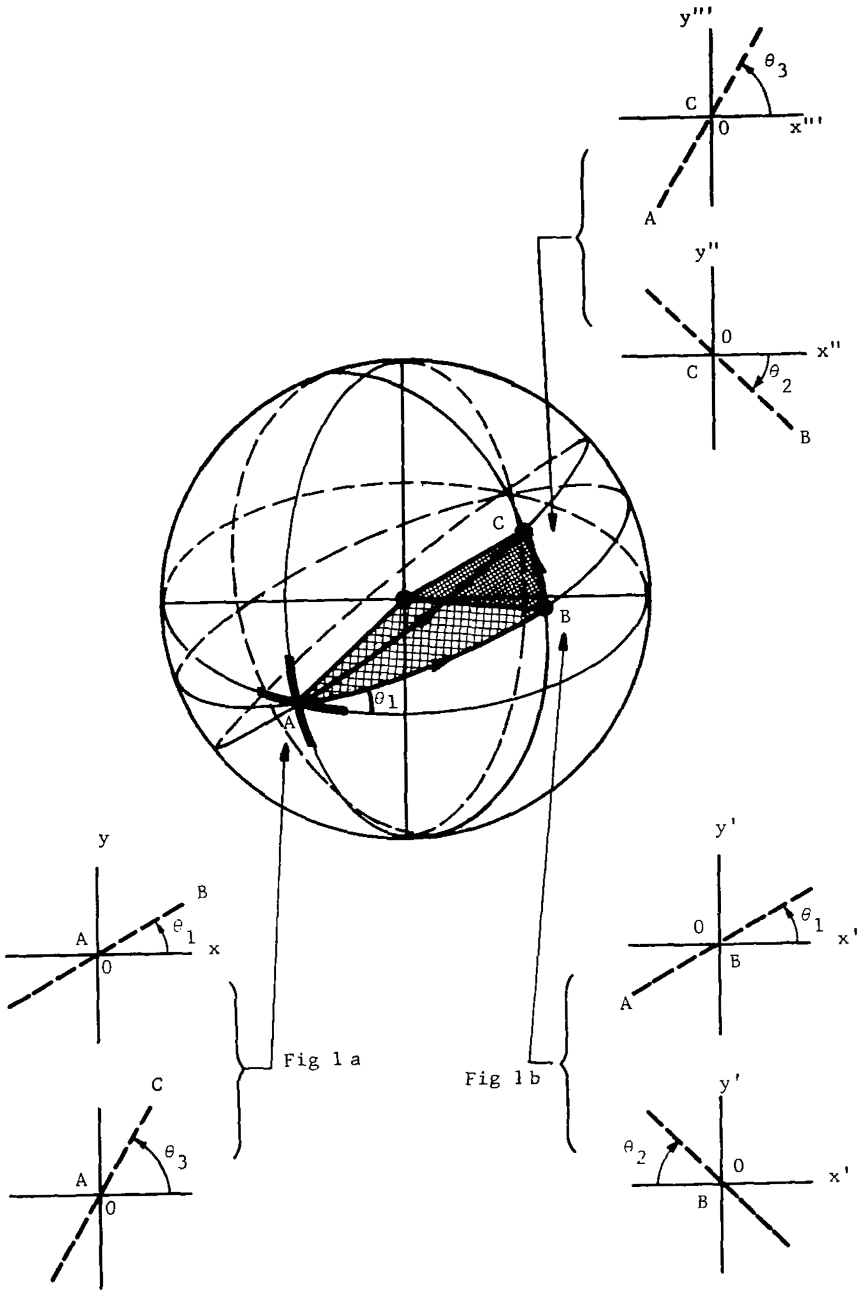


Figure C.1 EYE AND HEAD ROTATIONS

Now, let the eye be rotated (with no head motion) from the zero position directly to C. Let the great circle angle with OX'' be θ_3, as shown in Figure C. 1e and 1f.

Consider the angles in the spherical triangle ABC as in Figure C.2. Let the area of the spherical triangle be Z and the spherical radius r. Then, the sum of the angles of the spherical triangle is given by:

$$\angle A + \angle B + \angle C = \pi + \frac{Z}{r^2}$$

From Figure 2

$$\angle A = \theta_3 - \theta_1$$

$$\angle B = \theta_1 + \theta_2$$

$$\angle C = \pi - (\epsilon + \theta_2 + \theta_3)$$

where ϵ is the angle between OX'' and OX'''

$$\therefore \quad \angle A + \angle B + \angle C = \theta_3 - \theta_1 + \theta_1 + \theta_2 + \pi - (\epsilon + \theta_2 + \theta_3)$$

$$= \pi - \epsilon$$

$$= \pi + \frac{Z}{T^2}$$

$$\therefore \quad \epsilon = \frac{Z}{r^2}$$

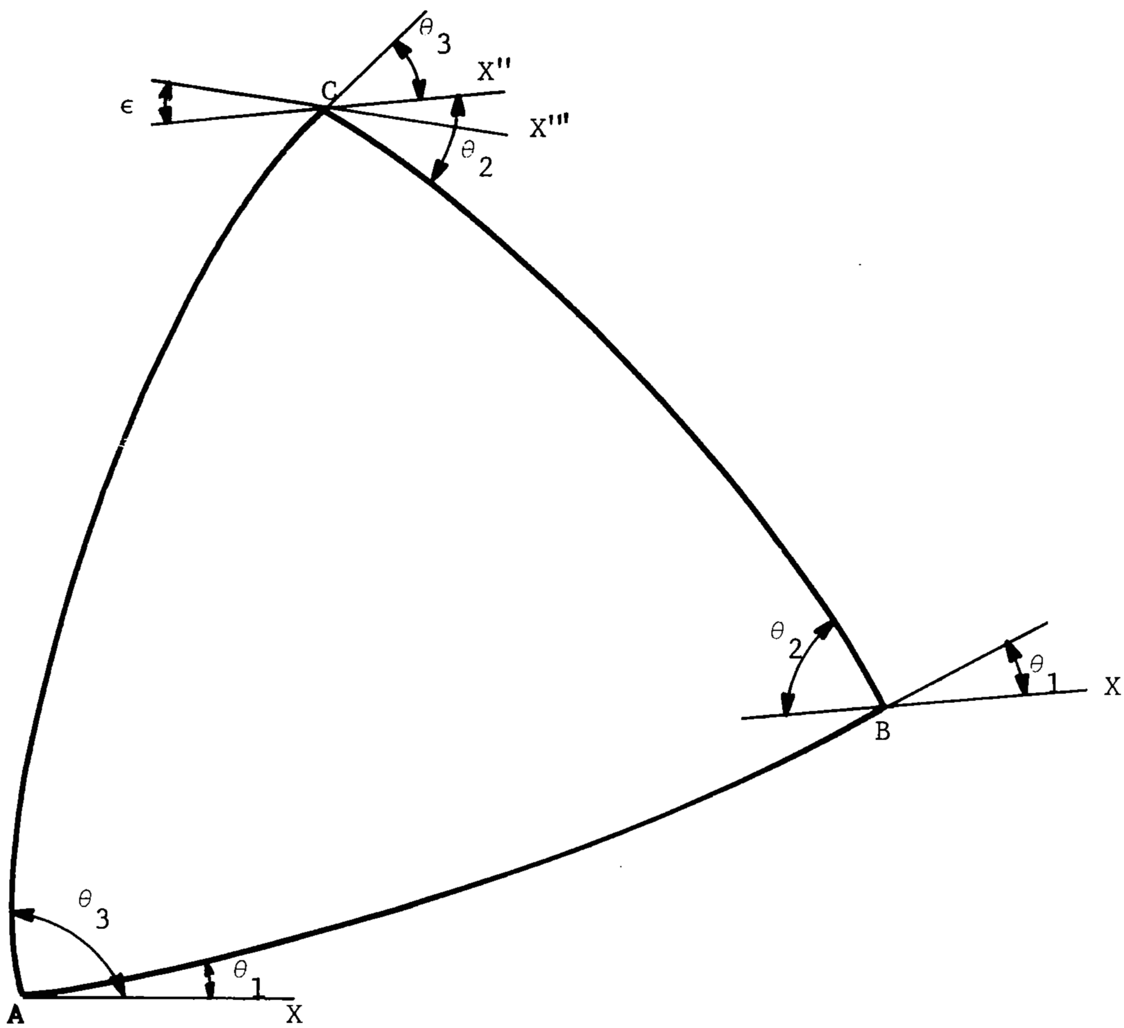


Figure C.2 SPHERICAL TRIANGLE

The angle ϵ represents a relative axial rotation of the eye (at C) between the two cases:

(a) Single pure eye rotation A to C

(b) An eye rotation A to B together with head rotation B to C.

The Oculometer would be calibrated in terms of a pure rotation from A to C. If, in fact, the optical axis of the eye appears at C as a result of the separate motions AB and BD, an error will be introduced, given by equation 1 where

$$\psi = \epsilon$$

Let the eye motion θ_e° and the head rotation θ_h°. Then, approximately

$$\epsilon^\circ = \frac{\theta_e \theta_h}{2} \frac{T_1}{180}$$

$$\approx 0.01 \theta_e \theta_h$$

The corresponding error in the location of the foveal axis is

$$\delta = 8.8 \times 10^{-2} \epsilon \approx 10^{-3} \theta_e \theta_h$$

The worst case eye fixation error (in degrees) as a function of head and eye rotation is given in the following table:

	Eye Angles (degrees)					
Head Angle (degrees)	5°	10°	15°	20°	25°	30°
5	.025	.05	.075	.1	.125	.150
10	.05	.1	.15	.2	.25	.3
15	.075	.15	.225	.3	.35	.45
20	.1	.2	.3	.4	.5	.6

For reference, 3 mils is equal to approximately 0.17 degrees.

4. Summarizing the Errors:

(a) Rotation of the head about the optical axis of the eye: 0.09 degrees error per degree of rotation of the head. (Errors due to rotations of the head about the optical axis can be corrected if both eyes are tracked, thereby defining the direction of the horizontal axis fixed in the head).

(b) Deviations from Listings Law.

0.025 degrees for moderate (normal) eye rotation

0.1 degrees due to convergence at an object 30 in. from the eye.

(c) Head rotations, other than in (a) above: See table in previous section.

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