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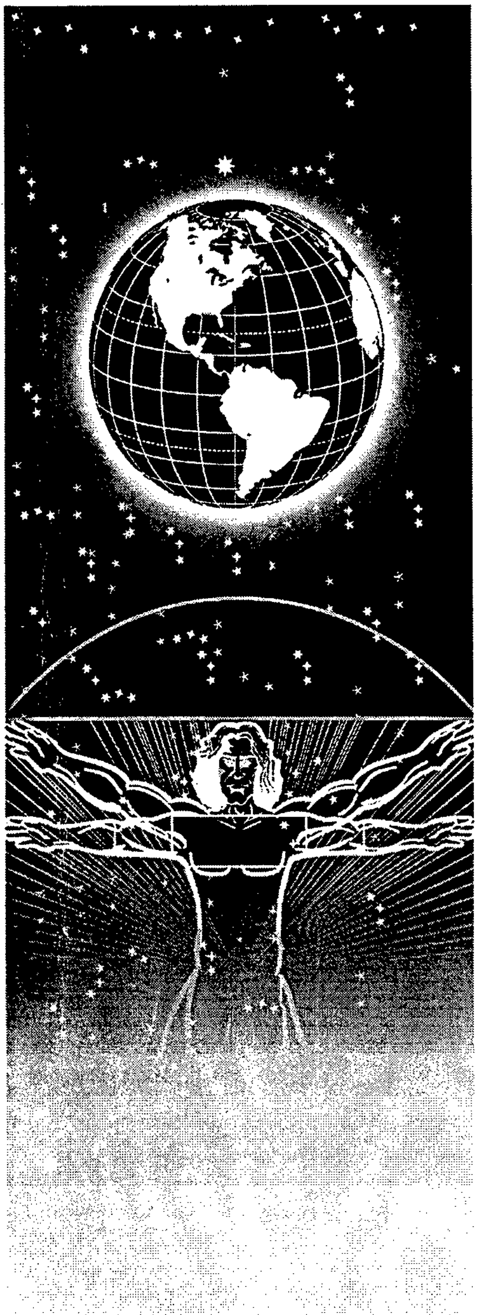

UNITED STATES AIR FORCE RESEARCH LABORATORY

HELMET-MOUNTED CONJUGATE OPTICAL DISPLAY SYSTEM: DESIGN CONSIDERATIONS

George A. Geri

Karl Frederick Arrington

Raytheon Training and Services, Inc.
6030 South Kent, Building 560
Mesa AZ 85212-6061

Milton J. Miller, Colonel, USAFR

Air Force Research Laboratory
Warfighter Training Research Division
6030 South Kent, Building 558
Mesa AZ 85212-6004

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AIR FORCE RESEARCH LABORATORY
HUMAN EFFECTIVENESS DIRECTORATE
WARFIGHTER TRAINING RESEARCH DIVISION
6030 South Kent, Building 561
Mesa AZ 85212-6004

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MILTON J. MILLER
Project Scientist

DEE H. ANDREWS
Technical Director

JERALD L. STRAW, Colonel, USAF
Chief, Warfighter Training Research Division

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George A. Geri; Karl Frederick Arrington; Milton J. Miller

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6030 South Kent
Mesa AZ 85212-6061

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Conjugate optical display systems (CODSs) have the potential for providing inexpensive, high-resolution imagery suitable for flight simulator applications. As with any display system, however, there are technical issues that have to be addressed before the system can be used effectively. We begin here with a description of the conjugate-optical principle as well as some basic data required to assess the optical properties of a CODS. We then discuss several perceptual issues relevant to the use of a CODS for presenting flight simulator imagery. Finally, we discuss some design considerations in selecting the optical components required to fabricate a CODS.

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PREFACE

The research described in this paper was conducted at the Air Force Research Laboratory, Human Effectiveness Directorate, Warfighter Training Research Division (AFRL/HEA), located in Mesa, AZ. This effort is documented under Work Unit 2743-B0-01, Warfighter Training Research Support, with support provided by Raytheon Training and Services Co. under contract F41624-97-D-5000. The Laboratory Task Monitor was Colonel Milton J. Miller, United States Air Force Reserve (USAFR); the Laboratory Contract Monitor was Mr. Jay Carroll (AFRL/HEA).

The authors thank Mr. Richard Olson (Lockheed-Martin) for interfacing and maintaining the video system used in the conjugate-optical display system (CODS), Mr. Tony Bailey for fabricating the bench CODS, and Ms. Lynnette Fischer for help in preparing the manuscript.

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HELMET-MOUNTED CONJUGATE OPTICAL DISPLAY SYSTEM: DESIGN CONSIDERATIONS

1.0 INTRODUCTION

Most terrain and objects viewed in real aircraft are located at effective optical infinity (i.e., at greater than about 30 feet). It has been generally assumed, therefore, that simulator imagery must also be at effective optical infinity to produce a realistic visual simulation. For this reason, optical collimators are used in many visual display systems. Among the collimation methods used in these systems are large spherical mirrors, multiple element windows, and various helmet-mounted, fiber-optical systems (Kelly, Shenker, & Weissman, 1992). There are several disadvantages associated with collimated visual systems including optical complexity, high-cost, and large size. In order to address the problems of optical complexity and high cost, a display system has recently been developed which uses commercial projectors and conventional rear-projection screens to present a simulated image at about one meter from the pilot (cf., Thomas & Reining, 1990). This system, however, is still relatively large and may result in certain perceptual problems related to the physical proximity of the imagery to the pilot (Pierce & Geri, 1998).

As noted above, the visual display systems employed in high-fidelity, full field of view flight simulators are typically either optically complex, or large, or both. However, a display system has recently been described, which could provide highly detailed, collimated imagery using relatively simple, lightweight, and inexpensive optical components. The system employs a conjugate-optical projector and a retroreflecting screen to place separate images at each of the observer's eyes (Fisher, 1992).

In addition to optical complexity, most helmet-mounted systems will overlay the simulated image on the instrument panel and elsewhere in the cockpit where the pilot might look. The conjugate optical display systems (CODSs) can significantly reduce this problem since the projected imagery is virtually undetectable unless projected against a retroreflective screen. Also, an individual CODS has the advantage that its imagery is, for the most part, not visible to observers other than the user. Thus, separate CODS could potentially be used to present imagery simulated from the slightly different viewpoints, as for example of the individual pilots in multipilot aircraft. On the other hand, as with any display device, there are also potential problems associated with the use of a CODS. For instance, the CODS uses a projected image that may be distorted at large distances from the center of projection. Further, these distortions may be exacerbated by the off-axis properties of the retroreflecting screen. Also, in a CODS, multiple projection sources will have to be mounted on a single helmet in order to attain a wide field of view ($>150^{\circ} \times 120^{\circ}$). In order to effectively use multiple projectors, each must be of low weight, and any associated optics must be chosen to allow image blending and to minimize obstructing the pilots view of both the retroreflecting screen and cockpit instruments.

We discuss here some optical and perceptual issues that we believe should be considered in designing future CODSs. We will first briefly describe the optical principles behind the CODS, and then summarize some measurements we have made in order to verify the properties of the projection optics and the retroreflecting screen. We will then discuss several perceptual issues related to field of view, depth perception, and the appearance of imagery displayed using a CODS. Finally, we will suggest some optical designs consistent with the identified perceptual limitations.

2.0 DEFINITION OF A CONJUGATE OPTICAL SYSTEM

2.1 Conjugate Points Relative to a Simple Lens

Consider an optical element, such as a glass lens, surrounded by air. Consider also a ray of light that originates in the air and impinges on the lens. Given these conditions, a portion of this ray will be *reflected* by the glass lens surface back into the air and a portion will be *refracted* into the lens. The laws of reflection and refraction state that: (a) the reflected ray will leave the lens surface at the same angle at which it impinged on the surface, and (b) the refracted ray will enter the lens at an angle that depends on the properties of the glass (or other substance) making up the lens. The *principle of reversibility* states that if the direction of a light ray is reversed after reflection or refraction, it will retrace its original path. Further, if parallel light rays are made to impinge on a lens, the rays will be refracted both upon entering and leaving the lens. With a convex lens the rays will converge to a point, called the *focal point,* on the other side of the lens. Similarly, by the principle of reversibility, light diverging from the focal point will be rendered parallel on the opposite side of the lens.

Applying the above-stated principles to the optical system shown in Figure 1, if the upper ray from the object (A) is parallel to the lens axis, that ray will pass through one focal point (F') after being refracted by the lens. Further, if the lower ray from point A passes through the other focal point (F), that ray will exit the lens parallel to the lens axis after being refracted. The point of intersection (A') of these two rays determines the location of the image and its size. By definition, the object and its image are located at *conjugate points* about the lens.

As shown in Figure 1, if an illuminated object is placed on one side of a convex lens, and farther away than the focal point (F), an image of the object will be formed on the other side of the lens. Again, from the principle of reversibility, the object and its image are interchangeable. That is, if the object were placed where its original image was located, its new image would be where the object originally was. In fact, the word *conjugate* literally means *interchangeable.* Note that if the object is moved closer to the focal point on one side

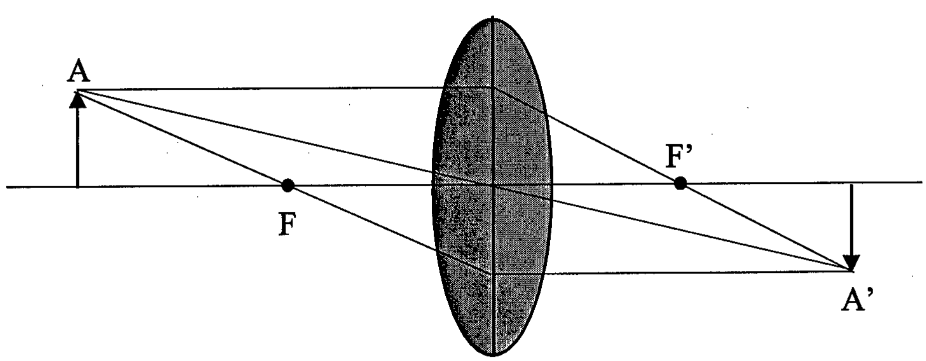
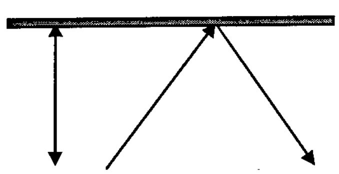


Figure 1. An Optical System Defining Conjugate Points About a Simple Lens.

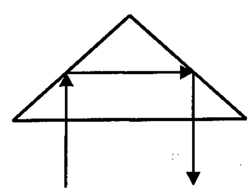
of the lens, then the image will move farther away from the focal point on the other side of the lens, and it will be magnified. The opposite is the case if the object is moved farther from the focal point. In either case, the pair of conjugate points will have changed, although the new pair will still be conjugate.

2.2 Retroreflecting Screens

At a typical reflecting surface such as a plane mirror, only light rays directed perpendicular to the surface are reflected backwards parallel to the incoming rays; all other rays are reflected in other directions (see Figure 2a). However, if two reflecting surfaces are placed at right angles (see Figure 2b) the incoming rays will be reflected twice, one by each surface, such that all rays will exit parallel to the incoming rays. Such an arrangement is called a *retroreflector.* This optical geometry is easily extended to three-dimensional space by using three reflecting surfaces that are arranged at right angles like the corners of a cube. In fact, this type of retroreflector is called a *cube corner retroreflector*.



a)



b)

Figure 2. A Plane Mirror (a), and A Prism Retroreflector (b).

If numerous, small prisms are etched or otherwise formed on the surface of a glass or plastic substrate, the surface will reflect light back very nearly along its original path, thus producing a retroreflective surface. A retroreflector can also be produced by embedding small plastic beads on a surface. Retroreflecting screens are routinely used, for instance, in traffic signs to increase the amount of light reflected directly back to a driver at night. Retroreflective material is available in large flexible sheets, and it can be mounted in many configurations.[1] We have measured several of the properties of retroreflecting screens, which are relevant to their use in a helmet-mounted CODS, and those data will be described later in this paper.

2.3 A Simple Conjugate Optics Display System (CODS)

Using the principles described above, we can produce a very simple optical system that will provide a conjugate-optical image. A schematic of such a system is shown in Figure 3. The liquid crystal display (LCD) is analogous to point A in Figure 1. The conjugate optical system, which includes the projection lens, the beamsplitter, the retroreflecting screen, and the optics of the observer's eye, is analogous to the lens of Figure 1. The display system of Figure 3 places an image of the LCD display on the observer's retina. In terms of optical geometry, the LCD display and the retinal image are interchangeable (conjugate), as were points A and A'.

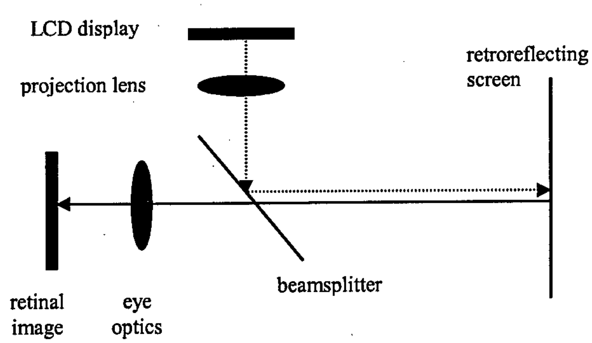


Figure 3. A Simple Conjugate-Optical Display System.

3.0 CODS COMPONENT EVALUATION

3.1 Bench CODS

In order to investigate some of the basic properties of the CODS, we designed and built a system that could be mounted on an optical bench, and that would allow us to vary the angle between the lines of sight of the two eyes (i.e., the binocular vergence angle). Photographs of the bench CODS are shown in Figures 4a and 4b. The test imagery was displayed on two, monochrome (green) CRTs. The imagery from both CRTs was projected using either a 16 mm or 25 mm CCTV lens (Edmund Scientific, Barrington, NJ) and was reflected by a large beamsplitter. In accordance with the principles described earlier (see Figure 3), the beamsplitter of the CODS directed a portion of the light to a retroreflecting screen that reflected the light back through the beamsplitter to the observer's eyes. The CRTs and associated electronics were designed to produce 1,000 lines^2 independently of each other, but for the present system evaluation, both CRTs displayed the same imagery, which was provided by a standard VHS video cassette recorder.

The level of ocular vergence can be specified as the angle formed by the lines of sight of the two eyes. Thus, when viewing (i.e., fixating upon) a distant object with both eyes, the vergence angle is small, but it increases as the distance to the viewed object decreases. Vergence could be changed in our bench CODS by varying the angle between the mounted CRTs (see Figure 4b). The retroreflecting screen was mounted such that both its angle relative to the observer's line of sight and its distances from the observer could be varied independently. Using the 25 mm projection lens and a retroreflecting screen distance of 36", the 1" diameter CRT provided an image over a field of view of about 31° × 24°.

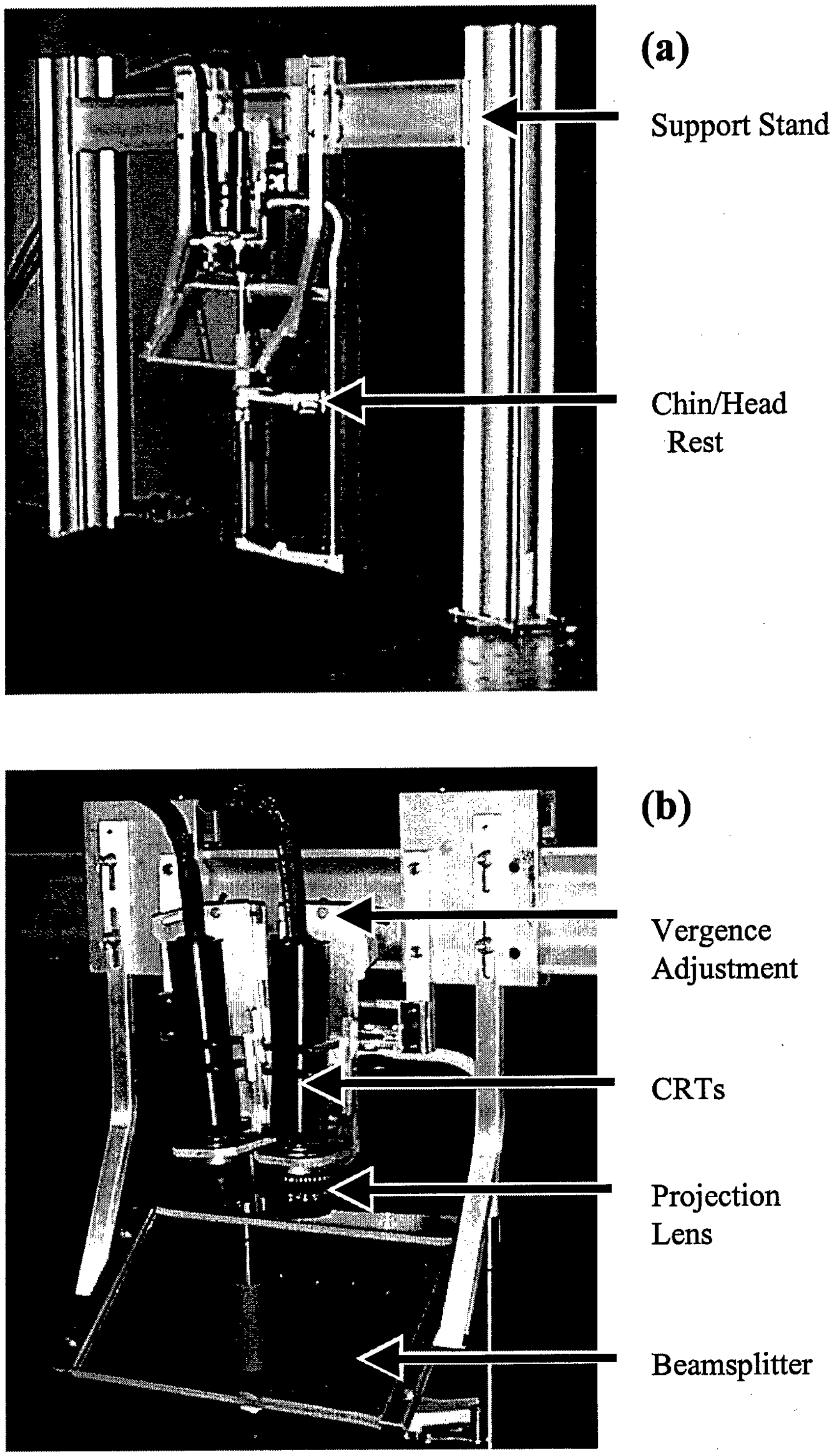


Figure 4. Bench CODS. (a) Full View; (b) Close-up of Optics.

3.2 Measurement of Retroreflecting Screen Properties

The directional properties of a retroreflecting screen can be characterized in two fundamentally different ways. Following the nomenclature used by one manufacturer[3], the *angular response* of a retroreflecting screen can be measured by aligning the source and detector and then changing the *entrance angle*, β, they make with the normal to the surface of the screen (see Figure 5, top). Another property, *reflective efficiency*, provides a more direct assessment of the retroreflecting properties of the screen, and can be measured by directing the source along a normal to the surface, and then varying the *observation angle*, α, of the detector relative to the normal (see Figure 5, bottom).

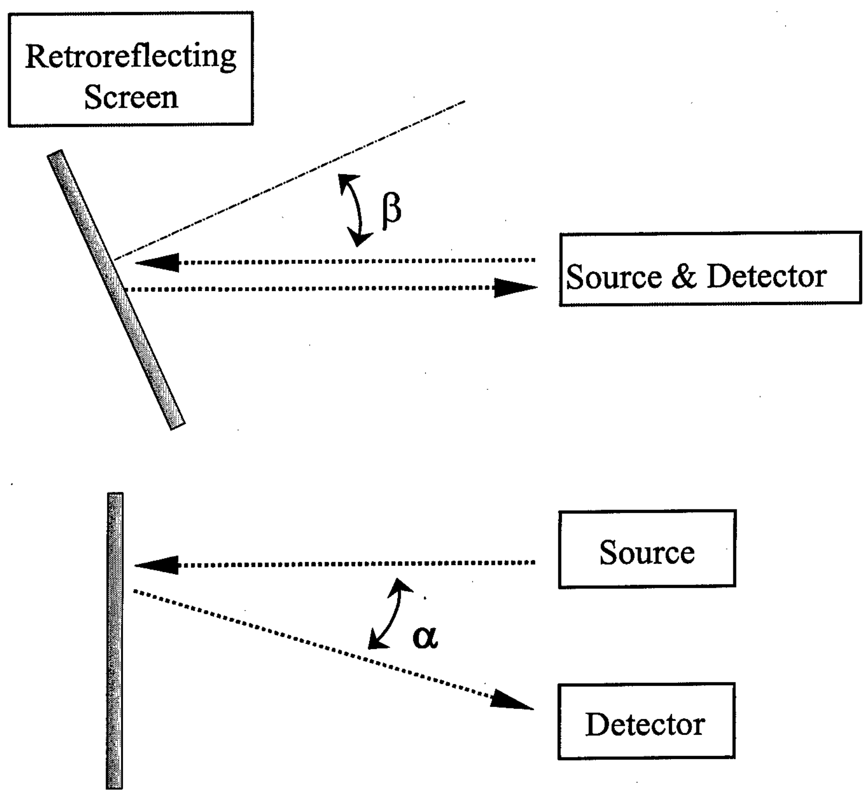


Figure 5. Configurations for Measuring the Directional Properties of Retroreflecting Screens. α *= observation angle,* β *= entrance angle.*

In the present study, angular response was measured by keeping the source and detector stationary and rotating the retroreflecting screen. The distance from the source to the screen was also varied. A PR-1500 Photometer (Photo Research Inc., Chatsworth, CA) was used for all measurements and was placed at the eye point. We did not measure reflective efficiency, although we have replotted, in polar coordinates, one manufacturer's data[3] (see Sect 5.5, p. 21).

3.2.1 Angular Response Curves

Angular response curves for the high-gain screen used in the bench CODS are shown in Figure 6. These curves show measured luminance as a function of the entrance angle β, between the detector/source and the normal to the screen (see also Figure 5, top). The data verify the well-documented properties of the retroreflecting screen for several viewing distances from 1.0 m to 3.0 m. At a given viewing distance, image luminance increases gradually with an increase in screen angle from 0° to about 25°. Image luminance then decreases for larger viewing angles, effectively asymptoting at about 60°. Although there is a significant decrease in image luminance with viewing distance, the general form of the function relating image luminance to viewing angle is the same for the various viewing distances tested. Thus, the decrease in image luminance with viewing distance, which is evident in the data of Figure 6, does not interact with the viewing angle.

In obtaining the measurements shown in Figure 6, we varied the observation angle using the source and detector configuration shown in Figure 5 (top). It would also be possible to use the component configuration of Figure 5 (bottom), and in addition change the entrance angle. The resulting data would then be determined by both of the retroreflecting screen properties described above. Specifically, data obtained with the source directed normal to the screen and the detector directed at various locations across the screen, at least along the horizontal meridian, would probably provide important information especially in characterizing wide-field CODSs. Data of this kind would also help to determine the extent to which angular response, reflective efficiency, and other measures of directionality may be a property of the CODS as a whole, as opposed to just the retroreflecting screen.

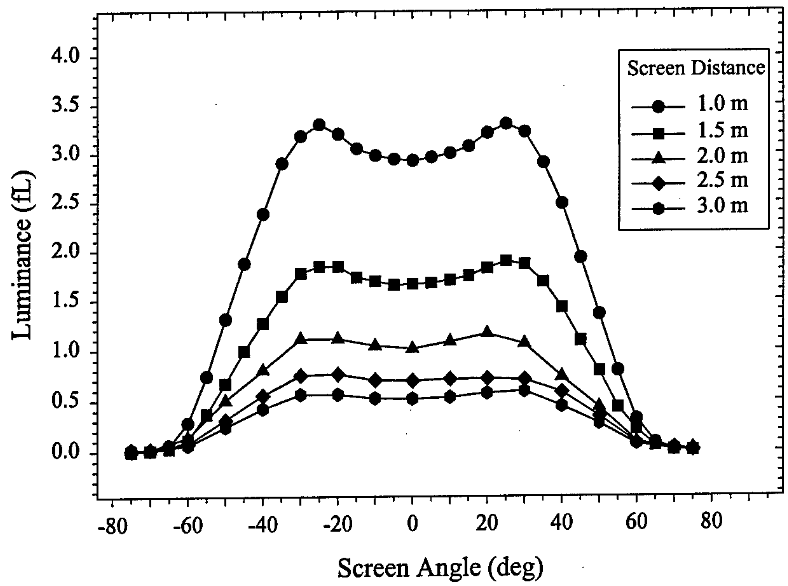


Figure 6. Angular Response Functions of a Retroreflecting Screen.

4.0 PERCEPTUAL EFFECTS RELATED TO CODS IMAGERY

4.1 Apparent Depth of CODS Imagery

One of the potential advantages of a CODS as compared to real-image or collimated-image displays is that both the apparent distance of a viewed image and the relative depth of objects (i.e., within the image at a given apparent distance) can be varied. The *apparent distance* can be altered by changing the vergence of the CODS (i.e., the relative angle of the left- and right-eye channels). The *relative depth* of objects, however, is a stereoscopic phenomenon, and producing it would require presenting different views of the image to each eye. Both types of perceived depth will be discussed below.

It is perhaps not surprising that if the right- and left-eye channels are set such that their respective images converge on the retroreflecting screen, then the projected image appears to the user to be located at the plane of the retroreflecting screen. If eye vergence is then reduced without changing the screen distance, the image appears behind the screen. In this latter case, if the edges of the screen are visible, the perceptual effect is one of viewing imagery through a window or aperture. This is true even for no convergence at the farthest screen distance that we used, which was about 20 ft. At distances greater than about 15 ft, the apparent separation between the screen "window" and the image plane is small and probably of no practical importance. However, the separation referred to above may be perceptually more salient for screens significantly larger than the one we used (about 3 ft × 2 ft).

4.2 Cue Conflict in Image Segmentation

The visual impression of depth is largely a consequence of the slightly different views of the world available to the two eyes. The slight difference between views is called *binocular disparity*, and the resulting perception of depth is called *stereopsis*. The visual system uses various cues to segment a visual scene into objects and surfaces. Two of the more salient segmentation cues are discontinuities in *stereoscopic depth* and discontinuities in *surface properties*, such as luminance, color, line patterns, and texture. Under most viewing conditions, objects at different depths also have different surface properties, and so the two cues are consistent. Under some viewing conditions, however, there may be differences in one of these properties but not the other, and in this case a *cue conflict* will occur. This type

surface occludes a more distant surface, portions of the farther surface may not be visible to one or both eyes. Again, these unpaired regions arise because each of the eyes has a slightly different view of the surfaces, and as a result each eye sees the surfaces occluded to different extents. The portion of a surface visible to only one eye is said to be *half-occluded.*

Researchers in the area of binocular vision often produce the perception of stereoscopic depth by using devices which present slightly different views of the same scene to the two eyes. These devices are called *stereoscopes* and are similar, in principle, to the 3D-viewers available commercially. A potential problem in using stereoscopes is that half occlusions can be produced which are not consistent with those that occur when viewing the same visual scene with two eyes in the real world. Half-occlusions of this kind are called *ecologically invalid*, whereas those that are consistent with vision in the real world are called *ecologically valid.* Shimojo and Nakayama (1990) have shown that under ecologically valid, half-occlusion conditions the unpaired portions of the viewed surfaces are always bound in depth to the more distant surface. By contrast, under ecologically invalid conditions the unpaired regions are seen alternately by the two eyes (a condition known as binocular rivalry) and appear to have ambiguous depth.

Examples of occlusion configurations that might be found under natural viewing conditions, and hence are ecologically valid, are shown in Figure 7. Shown at the top of the figure are the two eyes (left eye [LE] and right eye [RE]) of an observer who is viewing two surfaces–one surface is larger and farther from the observer than the other surface. Because the smaller surface occludes a restricted portion of the larger surface, this configuration is referred to as a "spot occluder." As can be seen from the sighting lines drawn in the figure, in this configuration two small portions (labeled "LE only" and "RE only") of the farther surface are each visible to only one of the two eyes. In addition, these two small portions of the farther surface are in the temporal visual field of the eye to which they are visible.

Another ecologically valid configuration is shown in the bottom diagram in Figure 7. For obvious reasons, this configuration is called a "window occluder." Again, there are two portions of the farther surface that are each visible only to one eye. In this configuration, however, the two portions are in the nasal visual field of the eye to which they are visible.

In order to be seen in stereoscopic depth, an object or surface must present slightly different views to the two eyes. However, as noted above, for both the spot occluder and the window occluder, there are portions of the image which are seen only by one eye, and which therefore cannot unambiguously be associated with either the nearer or farther surface. Despite this ambiguity, the half occluded regions described above are correctly seen as part of the farther surface. It has been suggested (Nakayama & Shimojo, 1990) that the resulting percept is related to the fact that the spot occluder and the window occluder are naturally occurring configurations that stimulate the two eyes in a way that humans have evolved to interpret veridically.

As is the case with a more conventional stereoscope, both ecologically valid and ecologically invalid occlusion configurations may be created using a CODS. The top diagram in Figure 8 shows a viewing situation that could result if the vergence angle of the two channels of the CODS is set so as to place the fixation plane nearer to the subject than the retroreflecting screen. If unpaired imagery is projected off the sides of the retroreflective panel, ecologically invalid half-occlusions will be produced. This near-vergence condition produces half-occlusions similar to those of a "spot occluder", which are in themselves perceptually valid. The problem arises because the binocularly unpaired projected imagery is, according to image *surface properties*, supposed to perceptually bind with the closer surface (see speckled texture areas in Figure 8). However, according to the *stereoscopic* half-occlusion cue, these same regions are supposed to bind to the farther surface (see marbled texture areas in Figure 8). Consequently, the image creates a cue conflict, and hence ambiguous depth cues and disconcerting visual imagery. By comparison, the viewing situation that results if the viewing angle of the CODS is set so as to place the fixation plane farther from the subject than the retroreflecting screen is shown in the lower diagram of Figure 8. In this case, unambiguous cues are provided by both the surfaces properties (texture in this case), and the half-occlusions.

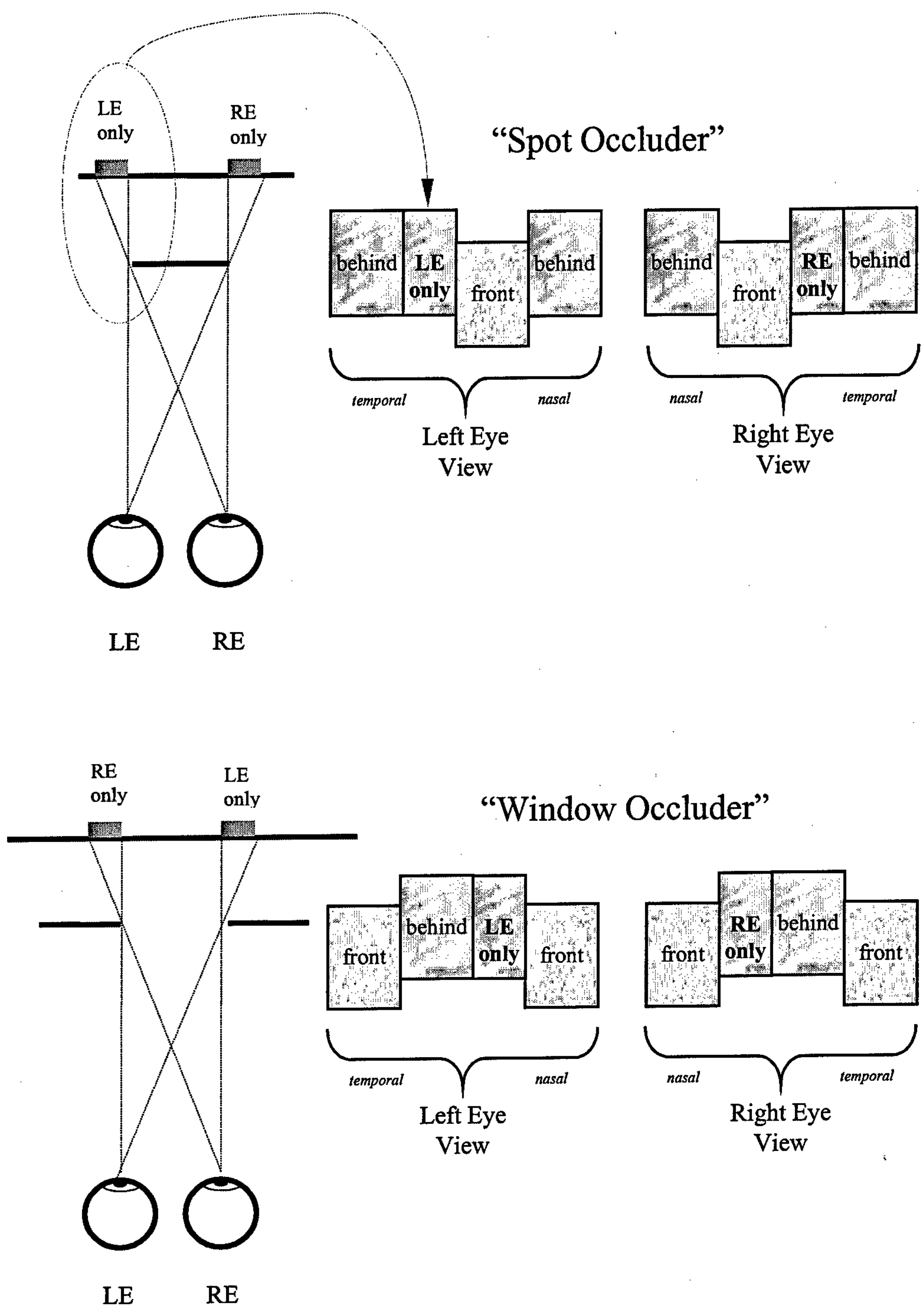


Figure 7. Half-Occlusion Viewing Conditions.

4.2.1 Recommendations

Based on these observations, we recommend that the CODS vergence angle be set so that the plane of fixation is at a distance greater than or equal to the distance of the retroreflecting screen (see Figure 8, bottom). As mentioned above, this configuration will give the impression of looking through a window, which is particularly appropriate for flight simulator applications. On the other hand, there are some situations, for instance when the system is used to display virtual instrumentation, in which it may be desirable to have the screen farther away than the fixation plan. In these situations, all of the nearer imagery must be reflected to both eyes (i.e., the screen must be larger than the visible projected imagery). If it is not, the half-occlusion imagery will create uncomfortable and unrealistic viewing conditions.

5.0 CODS OPTICAL DESIGN CONSIDERATIONS

5.1 Image Tiling to Increase Spatial Detail

In a helmet-mounted version of the CODS (Fisher, 1992), the same visual scene is displayed on two CRTs and is reflected and viewed through individual planar beamsplitters situated in front of each eye. Given that display devices currently available for helmet-mounted applications have relatively low pixel counts (i.e., at most 1280 × 1024), and given that at reasonable screen distances (see below) the imagery projected from a single source will in general not subtend more than about 45°, image detail high enough to support most flight simulator applications would require multiple displays, each subserving a portion of the required field of view. To obtain a larger field of view additional projection sources must be added. We will discuss next some of the issues that arise in using multiple projection sources in a CODS.

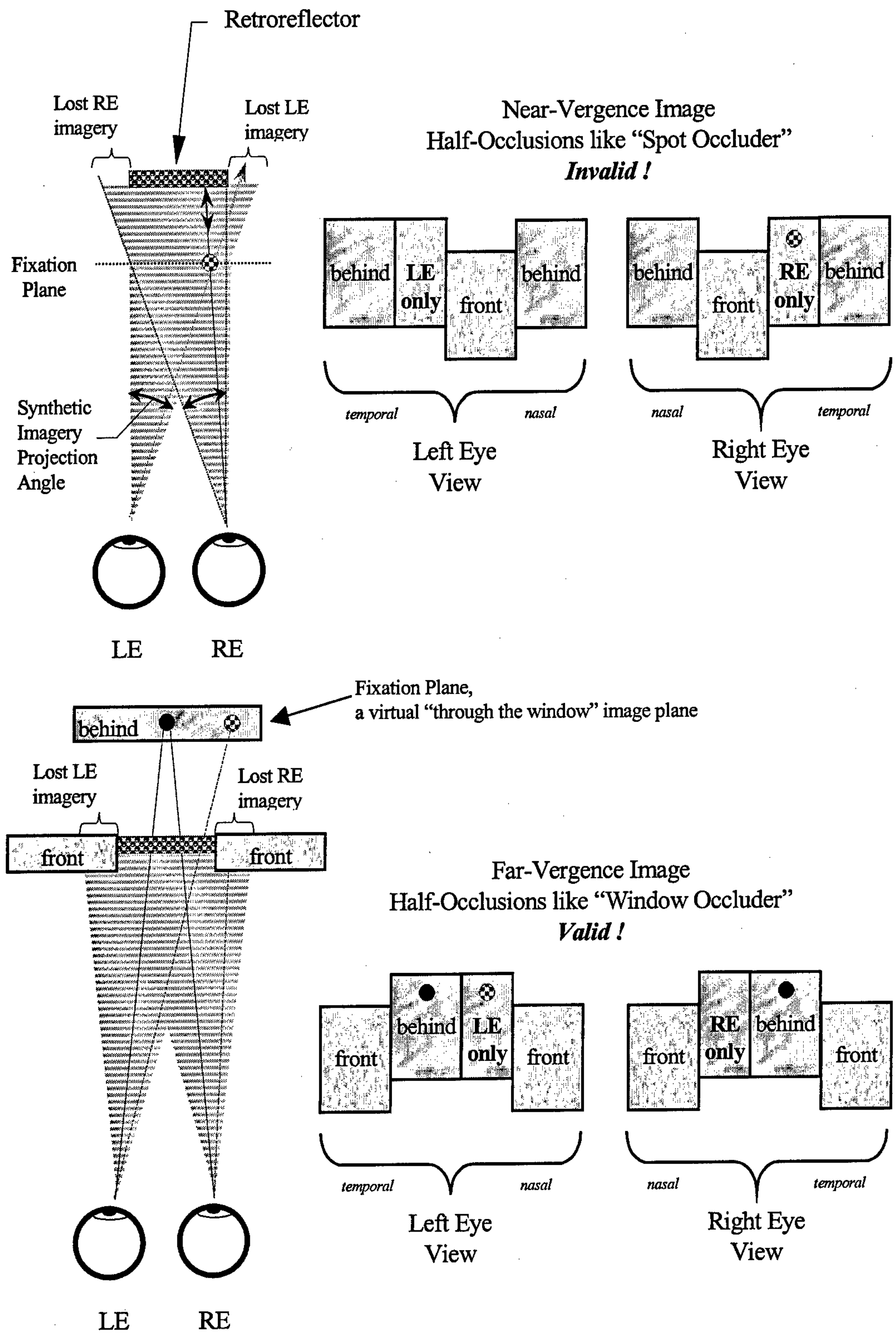


Figure 8. Cue-Conflict and Half-Occlusion

A conceptually simple method of optically tiling[4] multiple image sources in a CODS, would be to use two or more planar beamsplitters. A diagram of such a piecewise planar beamsplitter is shown in Figure 9. In the context of the CODS shown in Figure 3, one of the beamsplitters of Figure 9 might be positioned directly in front of one of the eyes, with the other beamsplitter located in the temporal visual field and thus presenting peripheral imagery. The most obvious problem associated with this beamsplitter configuration is the unavoidable seam between each adjacent pair of beamsplitters. It is expected that the visibility of these beamsplitter seams will be relatively low because they are located much closer to the eye than the imagery being viewed by the user, which will serve to blur the edges of the seam. Also, the seam will usually be located in the visual periphery (typically beyond 25°), because the CODS beamsplitters move with the head, and so the user's gaze will most often be directed through the center of the front beamsplitter even when imagery reflected from side screens is being viewed.

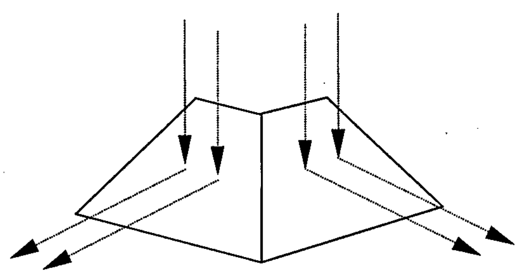


Figure 9. Piecewise-Planar Beamsplitter.

The problem of beamsplitter seams can also be avoided by using a curved version of the 45° planar beamsplitter, which would appear as a section of a cone with its pointed end removed (see Figure 10). A cone with its end removed is called a *frustrum*. One major consideration with using a frustrum in this application, however, is that the imagery is *reflected* off of the curved surface, which causes the image to diverge, much like a convex (e.g., fun house) mirror does. As a result of the principle of optical reversibility, the distortion is reversed (and hence removed) in the portion of the image returning from the screen, which is reflected again at the curved surface of the beamsplitter. However, the image viewed by the user remains distorted because it is transmitted rather than reflected at the curved surface. In order to remove the distortion in the viewed image, the inverse of the beamsplitter distortion function would have to be introduced into the generated image. This can be done relatively easily. Nevertheless, it is one more step that will have to be added to the image generation process, and separate calculations may have to be done for each beamsplitter.

We did not notice significant distortions with the planar beamsplitter used in either of our devices, although such distortions might be more obvious when higher resolution imagery is used. Again, however, given a head-tracked system, displayed imagery will be viewed primarily through the center of the front beamsplitter where distortion will be minimal. Further, any distortions of this kind in the imagery presented through the peripheral planar beamsplitters will probably not be visible. Further engineering analysis of the feasibility of the frustrum beamsplitter is recommended.

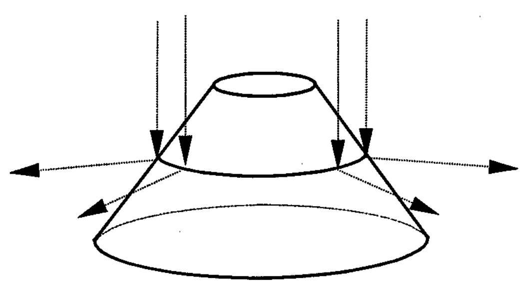


Figure 10. Frustrum Beamsplitter.

Visible seams are a problem associated with many rear-projection display screens. The CODS, of course, might also have seams between adjacent retroreflecting screens, although these will be much less conspicuous for two reasons. First, the retroreflecting material is much thinner and lighter, and more easily mounted than most projection screen materials. This allows the seams to be narrower, and makes it unnecessary to contend with obtrusive mounting hardware. In addition, in a CODS, the imagery on both sides of the seam will have originated from a single projector, thus reducing the differences in the image across the seam.

5.2 High-Resolution Image Source

As noted earlier, a 25 mm projection lens, a screen distance of 36", and a 1" diameter CRT provided a $31° \times 24°$ image in our CODS system. Clearly, several optical channels will be required to produce a high-resolution, wide-field CODS. Since multiple displays will be required and all image sources will have to be mounted on the same helmet, it is imperative that the display device be a *microdisplay* that is lightweight, bright, full color, and provide at least a $1K \times 1K$ image. Microdisplay technology is evolving rapidly and a solution suitable for a CODS may be available in the next year or two.

Many other technologies have been suggested for use as image sources in helmet-mounted displays, but it appears that none is currently capable of providing the required small pixel size in a sufficiently small package (Lowe, 1997). Another possibility has recently surfaced in the form of laser projection systems, but these are only in the very early stages of development (Glenn, Holton, & Dixon, 1997). Laser projectors are capable of small pixel sizes, but the optics and circuitry required to produce a usable raster are relatively complex. In short, as was the case when the first CODS was first proposed, the image source is the major obstacle to implementing this system.

5.3 The Retroreflecting Screen

As noted earlier, the data of Figure 6 were obtained using a relatively high gain screen, which means that the image luminance was selectively increased near the center of the screen at the expense of luminance at the edges of the screen. This function would be different for different screen gains. In addition, it should be noted that many types of retroreflective screens are flexible and can easily be applied to a curved surface. Suitably curving the retroreflective surface can also effectively change this function by reducing the variations in entrance angle, β. Of course, as is the case with all display systems, the screen chosen for a particular CODS system will be determined by the application.

It should be noted that significant specular reflection may occur when the projected image is close to normal to the retroreflecting screen. This specular reflection is caused by the surface material of the screen, and is not related to the retroreflection from the functional screen structure (glass beads, ridges, etc.). Our preliminary observations suggest that an incidence angle of about 3° or 4° from normal to the surface is sufficient to reduce specular reflection to acceptable levels. It is, in principle, possible to angle all screens in a CODS such that no portion of any screen is perpendicular to the user's line of sight. As a practical matter this will be easier to accomplish when simulating imagery for aircraft with smaller windows, each covering a relatively small field of view (e.g., a C-130). For aircraft simulations providing a wide field of view, the angle of the screens to the user's line of sight may have to be large, which may introduce other optical or perceptual problems related to the resulting differences in viewing distances to various portions of the screen.

5.4 Optical Quality Across the Field of View

The bench CODS described earlier (see Section 3.1) was constructed using inexpensive components which were not necessarily well-matched optically. In particular, the projection lenses were designed for use with video cameras and, therefore, did not accurately image the curved screen of the CRTs. This component mismatch resulted in a slight difference in focus across the displayed image, which we presume to be related to a slight curvature in the projected image plane. If a flat retroreflecting screen intercepts this curved plane at a tangent, then the imagery will appear to have best focus at the center and progressively worse focus in the periphery. We also noticed that imagery could be produced with poor focus at the center, better focus in an intermediate annular region, and poor focus again in the periphery. We attribute this latter condition to the screen intercepting the concave image plane at a point nearer to the observer than the tangent to that plane. It should be noted that the portion of the image that is out of focus will, in a head-tracked system, remain in the visual periphery where high detail cannot be seen in any case. This possibility could be investigated by checking to see if field of view changes at different viewing distances. Also, anyone designing a CODS might consider further investigating the effects on image homogeneity of both viewing distance, and of using less than fully overlapped binocular imagery.

5.5 Channel Crosstalk and Cyclopean Viewing

As noted earlier, the directional viewing properties of the CODS are largely a function of the reflective efficiency of the retroreflecting screen. Although we have described here only binocular CODSs, it is also possible to construct a cyclopean system wherein the imagery supplied by a single source is viewed by both eyes after reflection by the retroreflecting screen. Although this results in a simpler system, it does not fully exploit the potential of a CODS for presenting wide-field, stereoscopic imagery. Another limitation of the cyclopean approach is that, as a consequence of the reflective efficiency of the retroreflecting screen (see, Section 3.2), the imagery to each eye will be significantly reduced. The relative luminance under binocular and cyclopean viewing configurations is shown in Figure 11, where we have plotted in polar coordinates one manufacturers reflective efficiency data[3] for the retroreflective screen used in our CODS. The reflective efficiency plot shown in Figure 11 assumes a 200 cm eye-screen distance and a 6 cm interpupillary distance (IPD). The angular coordinates in the plot have been expanded by a factor of 60 so that the effects of small angle changes can be better appreciated.

In Figure 11, the projection and viewing angles associated with binocular viewing are indicated by the two solid double arrows. The double arrows labeled B_L, and B_R show the angular location of the source and receiver (i.e., eye) for the left- and right-image channels, respectively. Note that in this configuration the reflective efficiency is maximal. However, there is a potential problem with binocular systems in that the imagery associated with one eye may be visible to the other eye. This phenomenon is known as *crosstalk*, and it results in the appearance of "ghost" images. As can be seen from Figure 11, however, the amount of light directed to one eye and seen by the other is relatively small, although it may vary substantially with screen distance and IPD.

The projection and viewing angles associated with cyclopean viewing are indicated by the dashed arrows, labeled C-source, C_L-receiver, and C_R-receiver. In this case, the source is located between the eyes and the result is a significant reduction in image luminance to the two eyes. This is because the reflective efficiency function is such that in a cyclopean system the luminance fall-off is very steep at the observation angle between the source and receiver. Furthermore, in the cyclopean system, slight changes in the observation angle, as may result, for instance, from helmet slippage, will cause dramatic changes in the relative luminance levels to the two eyes. Moreover, the change in luminance will be in opposite directions, so the image to one eye will get much brighter while that to the other will get much dimmer. Given the inefficiency and instability of the cyclopean images to the two eyes we would not recommend this configuration for use in a CODS.

Finally, the data of Figure 11 indicate that reflective efficiency also has consequences in binocular CODSs. When two image projectors are used, one for each eye, there can be significant crosstalk between the signals to the two eyes. Again, the application will determine whether this is a significant problem.

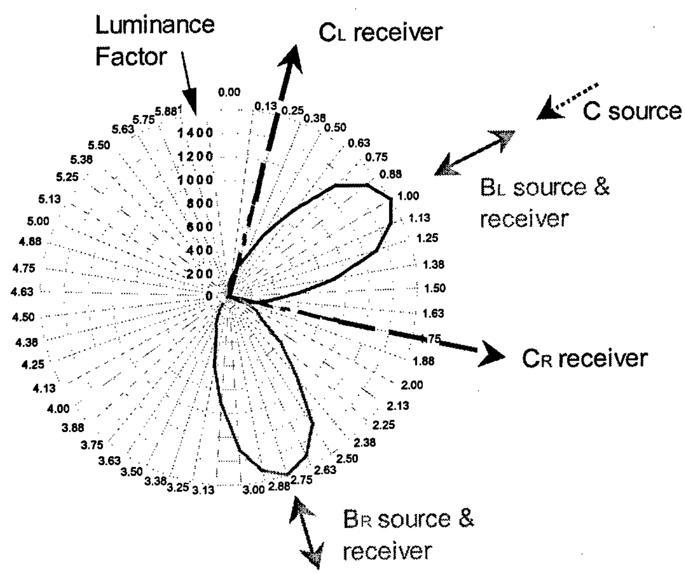


Figure 11. Cyclopean vs. Binocular Source-Receiver Relative Efficiency.

6.0 REFERENCES

Fisher, R.W. (1992). Head-mounted projection display system featuring beam splitter. *International Publication Number WO 92/18971, 29 October*; International Patent Application No. PCT/US92/03226.

Glenn, E.G., Holton, C., & Dixon, G.J. (1997). Laser-based electronic displays. *Proceedings of the SPIE, Projection Displays III,* **3013,** 21-26.

Kelly, G., Shenker, M., & Weissman P. (1992). Head-mounted area-of-interest display. *(AL-TR-1992-0119, AD A258 275).* Williams Air Force Base, AZ: Armstrong Laboratory, Operations Training Division.

Lowe, A. (1997). Matching display technology to the application. In L.W. MacDonald, & A.C. Lowe (Eds.), *Display Systems Design and Applications* (pp. 135-156). Chichester UK: John Wiley & Sons.

Nakayama, K, & Shimojo, S. (1990). Da Vinci stereopsis: Depth and subjective occluding contours from unpaired image points. *Vision Research*, **30**, 1811-1825.

Pierce, B.J. & Geri, G.A. (1998). The implications of image collimation for flight simulator training. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, 1383-1387.

Shimojo, S. & Nakayama, K. (1990). Real world occlusion constraints and binocular rivalry. *Vision Research*, **30**, 69-80.

Thomas. M.L. & Reining, G. (1990). The display for advanced research and training: An "inexpensive" answer to tactical simulation. In *ITEC--International Training Equipment Conference and Exposition Proceedings* (pp. 156-161). Warminster, Wiltshire, UK: ITEC Ltd.

7.0 NOTES

1. One manufacturer may be contacted at: Screen Products, 3M Center 220-7W-06, St. Paul, MN 55144. Phone: 612-733-4403.

2. The term "1,000 lines" here refers only to the video signal accepted by the display electronics. We have not measured the spatial resolution of this CRT, but it is unlikely to be 1,000 lines. Further, this is a monochrome system, whereas a high-fidelity CODS will require full color. See Section 5.2 for a more complete discussion of display devices that may potentially be suitable for use in a CODS.

3. See, *3M Special Effects Projection Screens*, 3M Industrial Optics Product Bulletin, 98-0439-4177-6(18.25)R1.

4. Image tiling as described here should not be confused with *image blending*, which is typically performed by the image generator for the purpose of minimizing the borders between adjacent images displayed using multiple projectors. In addition to providing a larger field of view, multiple projectors can also provide high-resolution insets composed of smaller but more highly detailed images. In order to be useful, these insets must be repositioned as the user's head (and preferably also eyes) moves, in order that they remain aligned with the high-acuity portion of the user's visual system. The CODS design in no way precludes image blending, which would in fact be particularly efficacious in this case since head tracking would already be implemented, thus assuring that the blended regions are kept in the visual periphery, and hence relatively inconspicuous.