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VISUAL DISPLAY SYSTEMS

by

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VISUAL DISPLAY SYSTEMS

1.0 Introduction

A flight simulator, as far as the pilot is concerned, needs to replicate to some unspecified degree the aircraft cockpit, the real world, and the interaction between the two. The purpose here is to describe the ways in which modern display technology can be brought to bear on the problem of generating an accurate rendition of the real world using Computer-Generated Imagery (CGI). It will be seen that display equipment, regardless of complexity or cost, is generally incapable of fooling the human observer. The imagery is always less than faithful by way of Field Of View (FOV), brightness, resolution, or some other quality issue. All one can hope for is that the pilot trainee will be too busy learning how to fly to notice incongruities in the visual scene before him; the trainee will hopefully use those limited visual cues provided by the scene to perform the training task. Interestingly enough, if the quantity of cues and overall fidelity of the scene is sufficient, then the mind of the trainee can be quite forgiving and will, in the best traditions of Gestalt psychology, fill in the additional information necessary for providing a feeling that it is indeed the real world in which he or she is training.

The job of the Visual Display Engineer is to ensure that the CGI is optimally presented to the trainee. This simple caveat hides the fact that optimality is not well defined. A wide range of image quality parameters enter into its definition, and in turn these are reflected in a broad selection of display hardware and configurations. Sorting through the pros and cons of favoring some quality parameters over others is not an exact science and will typically not imply a unique display configuration. As such, the attempt here will not be to establish a firm set of guidelines for specifying display systems for flight simulation. Instead, an appreciation will be cultivated for the limitations imposed by present-day display hardware and what this means in terms of trading off one set of display attributes for another as a function of specific training requirements.

2.0 CGI-Related Display Parameters

The material here is devoted to visual display systems for CGI. Since this particular type of image generation is discussed in more detail elsewhere, a full explanation of CGI will not be presented now. A cursory examination of its workings should suffice to provide an understanding of issues involved in its display to the trainee.

Producing a single channel of CGI fundamentally consists of mapping a rapidly changing 3-D world of objects into a 2-D image plane representing a desired FOV from a given eye location, much like taking a photograph. The mapped objects in the 2-D image plane would ideally be true to perspective with no distortion, have all spatial details faithfully reproduced (resolution), and have object appearance accurate with regard to visibility and ambient lighting (brightness), coloration, and obscuration by other objects. As it is, the hardware used for state-of-the-art CGI performs these functions remarkably well for large numbers of 3-D objects and does so at update rates necessary for providing the illusion of continuous motion (i.e., 50 or 60 Hz).

The five CGI parameters of most concern to the Display Engineer are FOV, ambient brightness, coloration, resolution, and output format. Distortion is not included since it is generally considered to be non-existent in the CGI; as such, the job of the display system is to faithfully render the scene geometry provided. There exist special situations, however, where the image generator (IG) will specifically distort imagery for some special purpose; e.g. to modify the spatial resolution of a projected image. In this case the display must remove the distortion bias so as to yield a perspectively accurate image for the trainee.

Returning to the five principal CGI parameters, the first— FOV—is significant because it scopes the magnitude of the optics involved. Generally, a larger FOV implies more elaborate and costly visual systems. The second parameter, ambient brightness, sets standards for the luminous output of the display input device and the optical efficiency of any subsequent optical components; e.g. lenses, mirrors, screens, etc. Daylight simulation will require more brightness than either dusk or night simulation. Large FOVs and high brightness are generally two incompatible goals. The third parameter, coloration, determines whether a monochrome, limited-color, or full-color display is required for taking full advantage of the CGI color capability. The fourth parameter, resolution, sets quality requirements on both the display input device and any additional optical components. Its value is often proportional to the size of display memory within the IG.

Output format, the fifth and final parameter, refers to the form in which image data is communicated to the display input device (or devices) by the IG. There exist a multitude of such formats, some of which are dignified as standards by the EIA; e.g., RS-170 and RS-343. Without getting too specific, the formats can be divided into two categories: raster and calligraphic. Raster is the more common of the two and is comparable to the method used in commercial television. Image information from the IG is read out as a series of parallel lines, with each line being read out sequentially pixel-by-pixel from left to right. Thus a picture might be constructed from left-to-right, top-to-bottom on a line-by-line basis until the entire image is displayed, as shown in **Figure 2.1**. The horizontal and vertical deflection signals are triggered by the IG, at which point the display is programmed to scan out the image in the required raster fashion. Concurrently the video (i.e., intensity) information is read out, timing being critical to ensure that the video information modulates the image at the instant that deflection addresses its respective location within the image.

In a calligraphic format, however, every pixel of video information has accompanying it an explicit (or implicit if only vector end points are defined) X, Y deflection value. Hence, a simple image can be displayed more quickly and accurately since only those pixels used are addressed, and these possibly can be addressed in a more efficient manner than that obtainable with a rigid raster structure (See **Figure 2.2**). The term "calligraphic' is derived from the controlled manner in which the display device draws the image, in a manner presumably reminiscent of fine handwriting. As will be discussed later, a calligraphic display is generally a more complex and expensive device than a raster display and does not necessarily perform better than the raster device in all respects.

Even though the preceding discussion implies that CGI characteristics set display requirements, such is generally not the case. Specifications of IG and display performance are usually formulated in parallel. The capabilities and limitations of each component are weighed against one another until an optimum compromise consistent with pre-defined training objectives is reached.

3.0 Measuring Display Parameters

A knowledge of how display parameters are measured is necessary for understanding eventual system performance. Eight parameters will be discussed now, of which all but the last are based on the previously mentioned CGI parameters. These are (i) FOV, (ii) brightness, (iii) contrast, (iv) resolution, (v) color, (vi) color convergence, (vii) geometry, and (viii) collimation distance. Color convergence is usually measured directly on the display input device or some intermediate viewing screen. The other six items are typically measured from the design eyepoint of the display system; i.e., the point at which optical performance is optimized and thus the preferred location for the pilot trainee. Furthermore, a guaranteed level of performance is usually required over a volume of space centered on the eyepoint. This volume should be at least 3 inches across since that is roughly the spacing of the trainee's eyes. If lateral or longitudinal head motion is commonplace during a training exercise, then the specified viewing volume must be correspondingly larger.

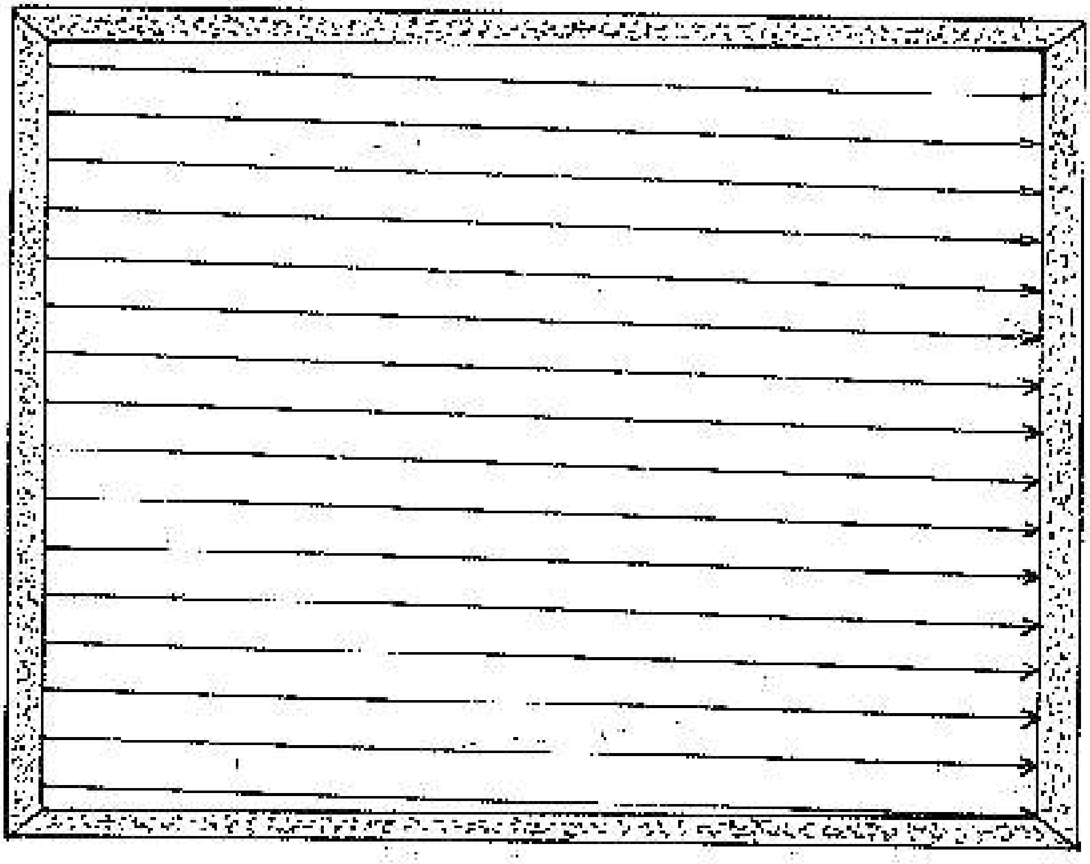


FIGURE 2.1 RASTER SCAN PATTERN.

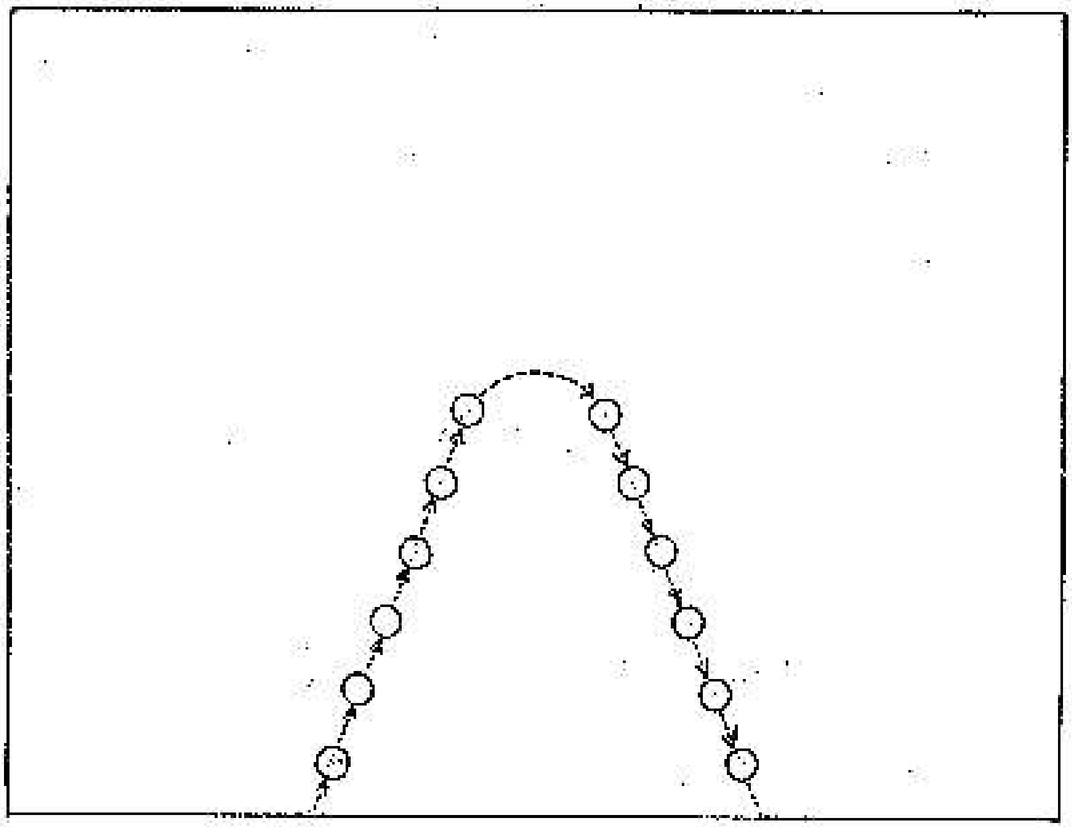


FIGURE 2.2   CALLIGRAPHIC WRITING SEQUENCE FOR RUNWAY EDGE LIGHTS

3.1 Field-Of-View

Display FOV is usually measured with a surveyor's transit positioned at the design eyepoint. By determining viewing extremes in elevation and azimuth, a sketch called a Field Plot (an example is illustrated in **Figure 3.1**) may be generated. Such field plots exist for actual aircraft as measured from the pilot's eye position. Comparing the Field Plots of the actual aircraft and simulator display is an excellent technique for determining the applicability of a particular display configuration to a particular aircraft.

3.2 Brightness

Measuring brightness takes one into the subject of photometry, which rightfully deserves a full course of its own. For simplicity, it is adequate to concentrate on three photometric units: the lumen, foot candle, and foot-Lambert. The lumen is a measure of luminous flux and is proportional to the power available for stimulating the human eye; i.e., it is comparable to the radiometric power measure in Watts but is spectrally weighted to take into account the varying sensitivity of the eye as a function of wavelength (see **Figure 3.2**). Often projectors will be rated according to their peak lumen output. The foot candle is a measure of illuminance (power per unit area) and corresponds to one lumen per square foot. This unit is often used to express the amount of light incident on a projection screen. The foot-Lambert measures luminance and corresponds to emission of one lumen per square foot from a perfectly diffuse radiator (one without a preferred direction of radiation). Luminance—also termed brightness—is the unit of choice for measuring brightness at the design eyepoint. It is also commonly used for expressing the brightness of a CRT display. A valuable characteristic of luminance is that a surface's value will be independent of the distance from which the measurement is made.

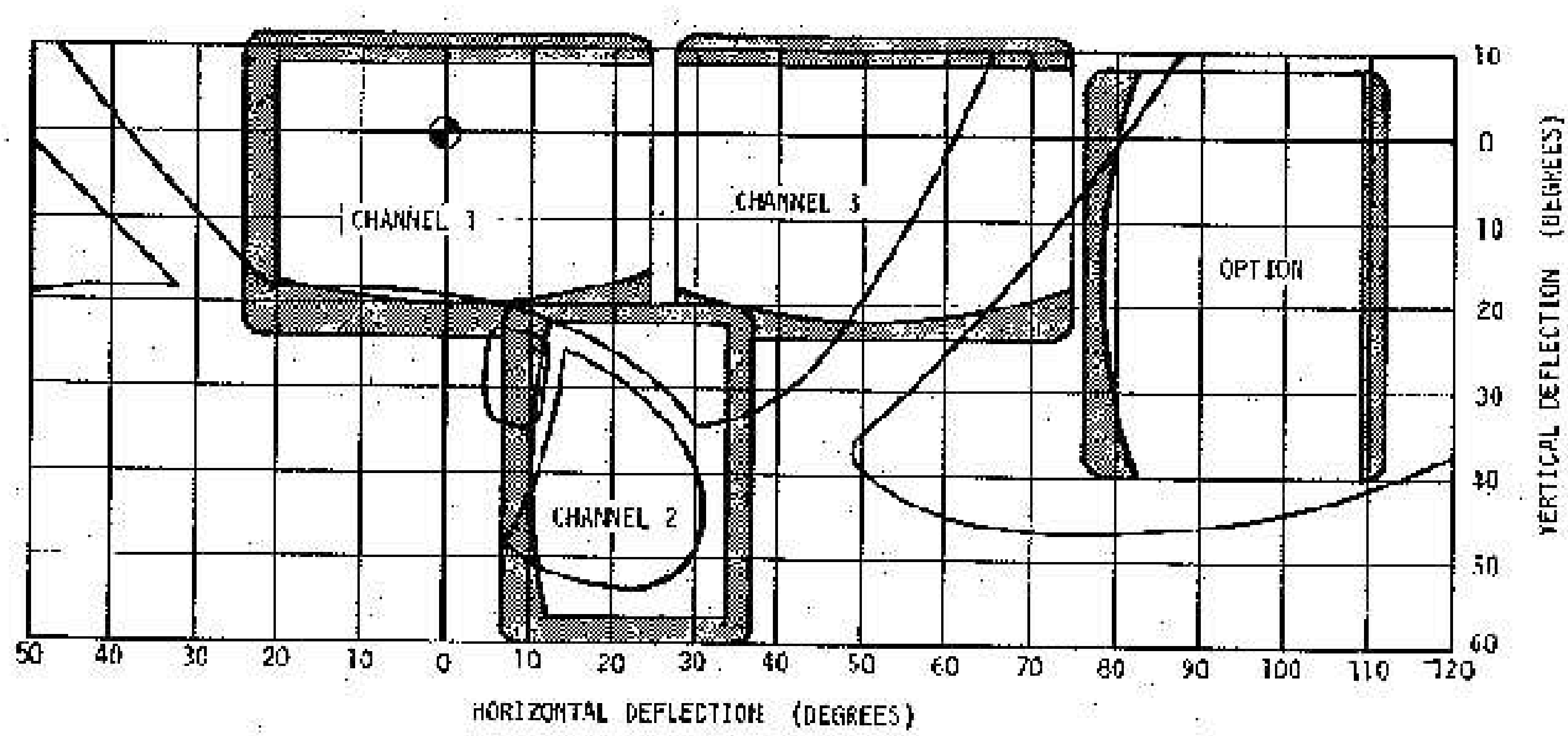
Only the latter two units, foot candle and foot-Lambert, are actually measured directly. This is done using either an illuminance or luminance meter (respectively). An illuminance meter, such as the one in **Figure 3.3**, incorporates a photodetector in conjunction with a diffuser acting as a cosine receptor; i.e., one whose sensitivity falls off as the cosine of the angle of deviation from a direction normal to the diffuser surface. **Figure 3.4** (Ed. Note: not available) shows a luminance meter. This device uses a sampling aperture (generally 1 degree or less) in conjunction with a photodetector. The sampling aperture is aligned with the luminous surface of interest using a view-finder, after which a measurement can be made. In evaluating a display, measurements are performed from the design eyepoint and are repeated at several points in the image to determine not only peak brightness but brightness uniformity as well.

3.3 Contrast

Contrast is a measure of the range of intensities available to a display system. This is reflected in its definition, which is

$$(IMAX - IMIN)/IMIN$$

where IMAX is the maximum displayable intensity and IMIN is the minimum displayable intensity. A measurement is performed by first displaying an image containing both white and black features and then measuring the brightness from the design eyepoint using a luminance meter. The test image is often a black square against a white background or white square against a black background. Sometimes both will be specified to determine if the display favors either predominantly light or dark imagery. Contrast values of 10 are adequate, but values in excess of 30 are not unusual.



NOTES:

DENOTES TOTAL FIELD OF VIEW

CHANNELS 1, 3 AND OPTION PRESENT 36° x 48° TOTAL FOV
CHANNEL 2 PRESENTS 30° x 40° TOTAL FOV

FIGURE 3.1 FIELD PLOT FOR S-76 HELICOPTER

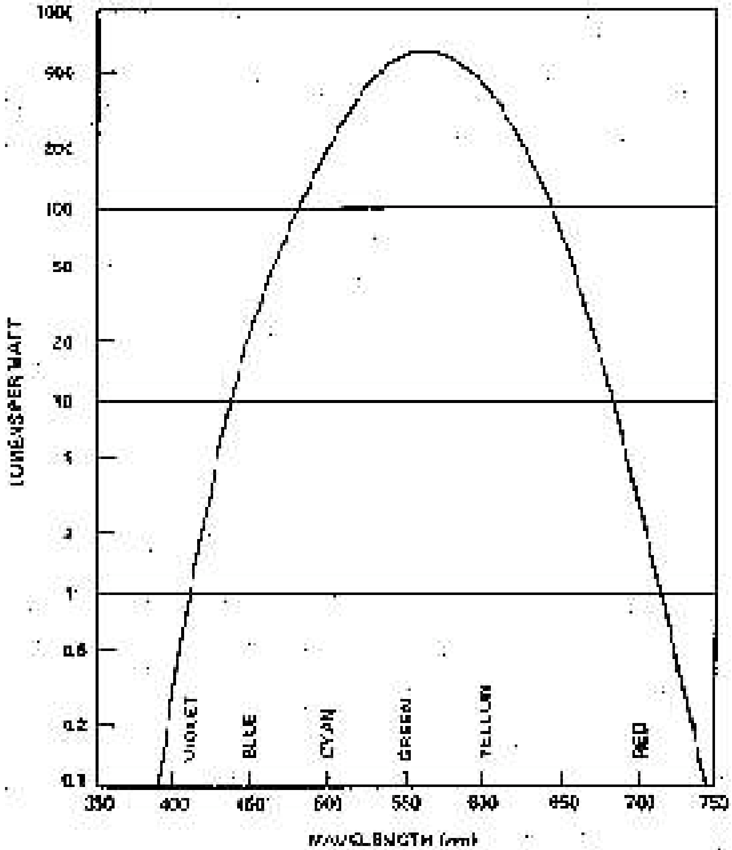


FIGURE 3.2   PHOTOPIC SPECTRAL LUMINOUS EFFICIENCY OF THE EYE

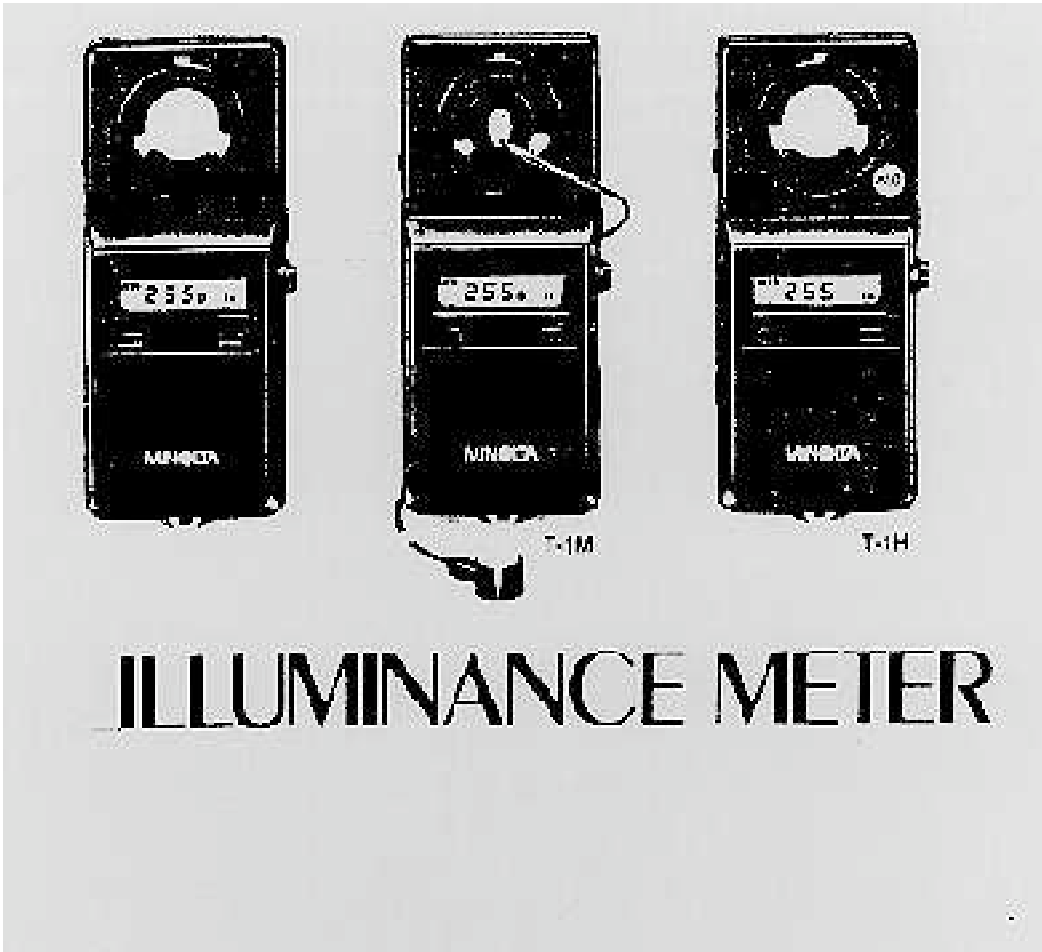


FIGURE 3.3 ILLUMINANCE METERS

3.4 Resolution

Resolution is a measure of the smallest image detail that can be discerned by an observer. Typically it is influenced by a wide range of parameters, including the number of picture elements per image computed by the IG, type of display, brightness, and overall video bandwidth. Resolution will generally be different as a function of horizontal and vertical direction, location in the image, and whether the image is static or dynamic.

There are several ways of designating resolution, all of which require careful definition. One nomenclature that is a carry-over from the TV industry is "TV lines". A display with 600 TV line resolution both vertically and horizontally implies that the number of lines just discernible per picture height is 600. For a standard TV tube with 4:3 aspect ratio, the number of resolvable lines its thus 600 vertically and 800 horizontally. Put yet another way, the number of resolvable picture elements, or pixels, is 600 vertically and 800 horizontally, making for a total of 480,000 displayed pixels. Some argue, however, that resolution is best measured using full cycles of information. In the preceding example, the resolution becomes 300 line pairs per picture height.

Often a resolution specification will be couched in terms related to measurements made from the design eyepoint of the display system. In the previous example having 600 pixels vertically by 800 pixels horizontally, assume that the FOV subtended at the eyepoint by the display device is 30 degrees by 40 degrees. Dividing each angle by the appropriate number of pixels yields a rough estimate of the resolution expressed in terms of angular units per pixel; i.e., 0.05 degrees per pixel or, more commonly, 3 arc minutes per pixel in both the horizontal and vertical directions. Alternatively, multiplying by two yields a value of 6 arc minutes per line pair, where this value denotes resolution based on a full cycle of information.

Measuring resolution is generally done in one of two ways. The first involves a spatially scanning slit photometer that scans across a displayed vertical or horizontal edge having maximum achievable contrast. The edge will have some finite rise or fall time which is a measure of resolution. Though very accurate, it requires expensive, specialized equipment and careful calibration. The alternate method is more direct and based on a subjective assessment rather than hard data. The IG is used to produce an image consisting of alternating white and black stripes or bars with maximum contrast; only a single set with known bar width and spacing is required. Since the environment is a flight simulator, one need only position the eyepoint so the observer is looking directly at the bar pattern and then back away from it until the individual bars are just resolvable; any farther and the pattern looks uniformly gray. Based on the bar pattern dimensions and the distance from the eyepoint to the pattern, a value for resolution may be assigned. For example, consider the pattern in **Figure 3.5**. The bar widths are 10 feet and the bar spacings are also 10 feet. It is found that the bars remain just visible out to a distance of 3500 feet. The angular extent of one cycle (bar plus space) is 2 arctan (10/3500) = 0.33 degrees, or roughly 20 arcmin. Hence the resolution is 20 arcmin per line pair, or 10 arcmin per pixel.

3.5 Color

The capacity to display various colors is particularly important in flight simulation since many of the visual cues needed by pilots have characteristic colors; e.g. the red and white of VASI lights, the blue of taxiway lights, the blue/brown or blue/green contrast of a shoreline used for navigation, and the white threshold stripes of a runway. The number of displayable colors can be measured by creating an IG model containing surfaces of all possible colors. If a requirement exists for the capability to simultaneously display 256 colors, then a patchwork of 256 squares (16 by 16) can be modeled, displayed, and viewed from the design eyepoint. If the observer can distinguish all 256 colors and no repetition is apparent, then the requirement is satisfied.

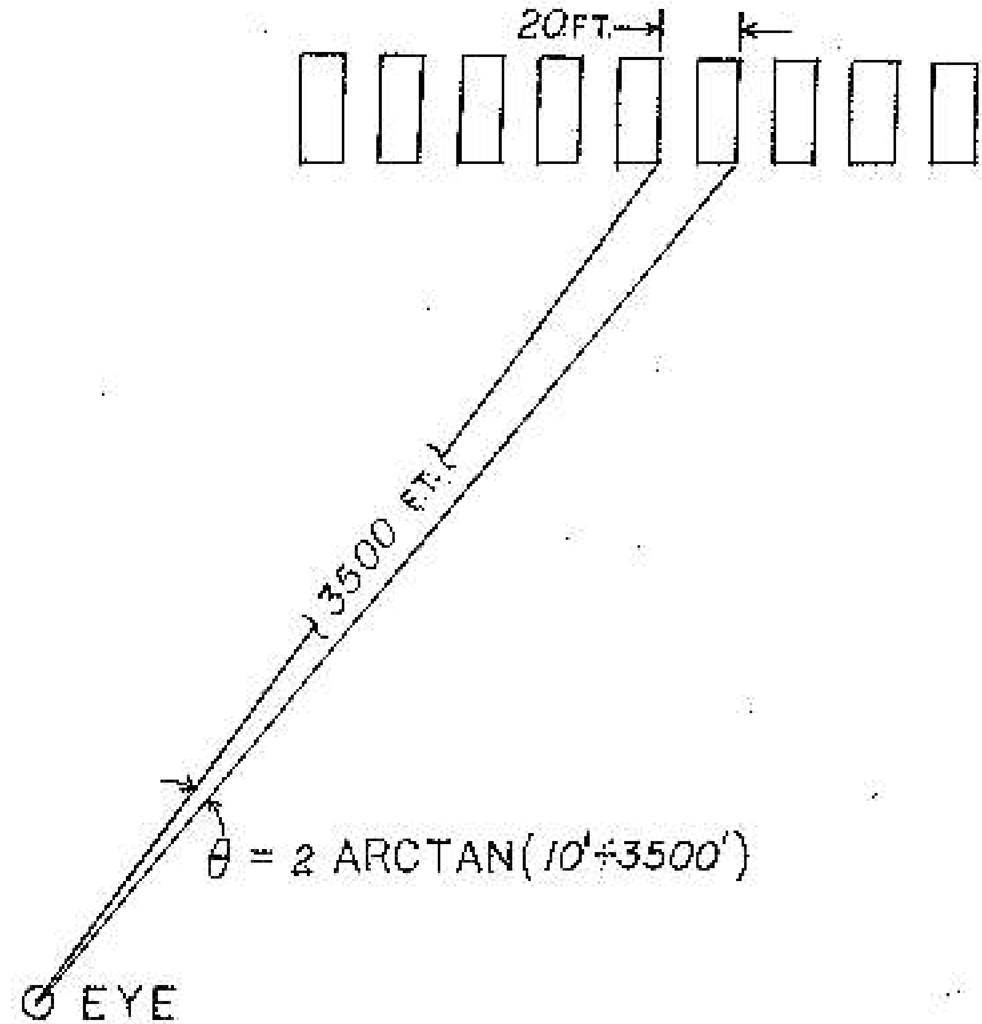


FIGURE 3.5 MEASURING RESOLUTION USING A BAR PATTERN

3.6 Color Convergence

Color convergence is an issue with any display system generating more than a single spectral color. It is a measure of how well the color components of each pixel align. For example, consider a white light being generated on a screen by a projector having three CRT projection tubes: red, green, and blue. The white light results from exactly overlaying red, green, and blue lights, each contributing 30%, 60%, and 10% of the total brightness, respectively. In practice, however, the three components are not exactly coincident. The resulting misalignment, termed "misconvergence", will manifest itself as a white light of reduced size with some degree of color fringing corresponding to areas of incomplete overlap. Misconvergence needs to be minimized since, in addition to degrading color purity, it limits displayable resolution as well.

It is generally appropriate to measure misconvergence at the screen or display input device rather than from the pilot's eyepoint. A ruler or magnifier with calibrated reticle is used to directly measure the separation among the centers of the three color components. Misconvergence is usually dependent on location within the image, being largest in the corners and smallest at the center. Display convergence is generally considered adequate if (i) convergence is near-perfect in the central region and (ii) misconvergence is no worse than the size of the smallest displayed object (e.g., a light point) anywhere else in the image. Measurements of convergence from the eyepoint are only required if the intervening optics are not color-corrected, thus tending to refract the colors differently and leading to a worsening of convergence over and above that caused by the display input device.

3.7 Geometry

Geometry reflects on the ability of a display to accurately portray shapes and positions of objects in an image. Straight lines should appear straight; objects equally spaced should appear equal distances apart. Deficiencies in this area can result in the pilot trainee not being able to accurately judge distance, speed, and height. Geometric distortion is generally measured by using a transit located at the design eyepoint to measure the grid-point locations of a displayed grid test pattern. Azimuth and elevation of the grid points are measured with the transit and compared to the modeled grid-point locations as defined by the test pattern. Any angular deviation from the theoretically correct location represents geometry error. This angular error is usually expressed either as a percentage of picture height or as a percentage of net deflection angle for the grid-point under consideration. A maximum geometric error of ±2% of picture height is considered quite acceptable in most training applications.

3.8 Collimation Distance

Collimation distance is a measure of how far the imagery appears to be from the trainee. In many display systems in which the trainee is viewing either a monitor or projection screen, the collimation distance is simply the distance between the trainee and image surface. In others, however, intermediate optics may be used to bend light rays so the rays appear to be coming from a more distant location. With this latter arrangement the trainee is viewing a "virtual" image; i.e., an image that appears to be originating in a location at which light is neither focussed nor generated.

The standard method for measuring collimation distance is to use a special transit consisting of two scopes separated by the interpupillary distance—about 70 mm. One of the scopes can pivot so as to adjust the angle between the two scopes. The transit is positioned at the display system's design eyepoint, and both scopes are centered on a common point in the image (usually a light point). For a perfectly collimated display in which objects are meant to appear at a near-infinite distance, the angle needed between the two scopes to simultaneously center the light is zero degrees; i.e., the scopes are parallel (see **Figure 3.6**). This is comparable to a human observer fixating on a distant object; both eyes are looking straight ahead without any inward tilt.

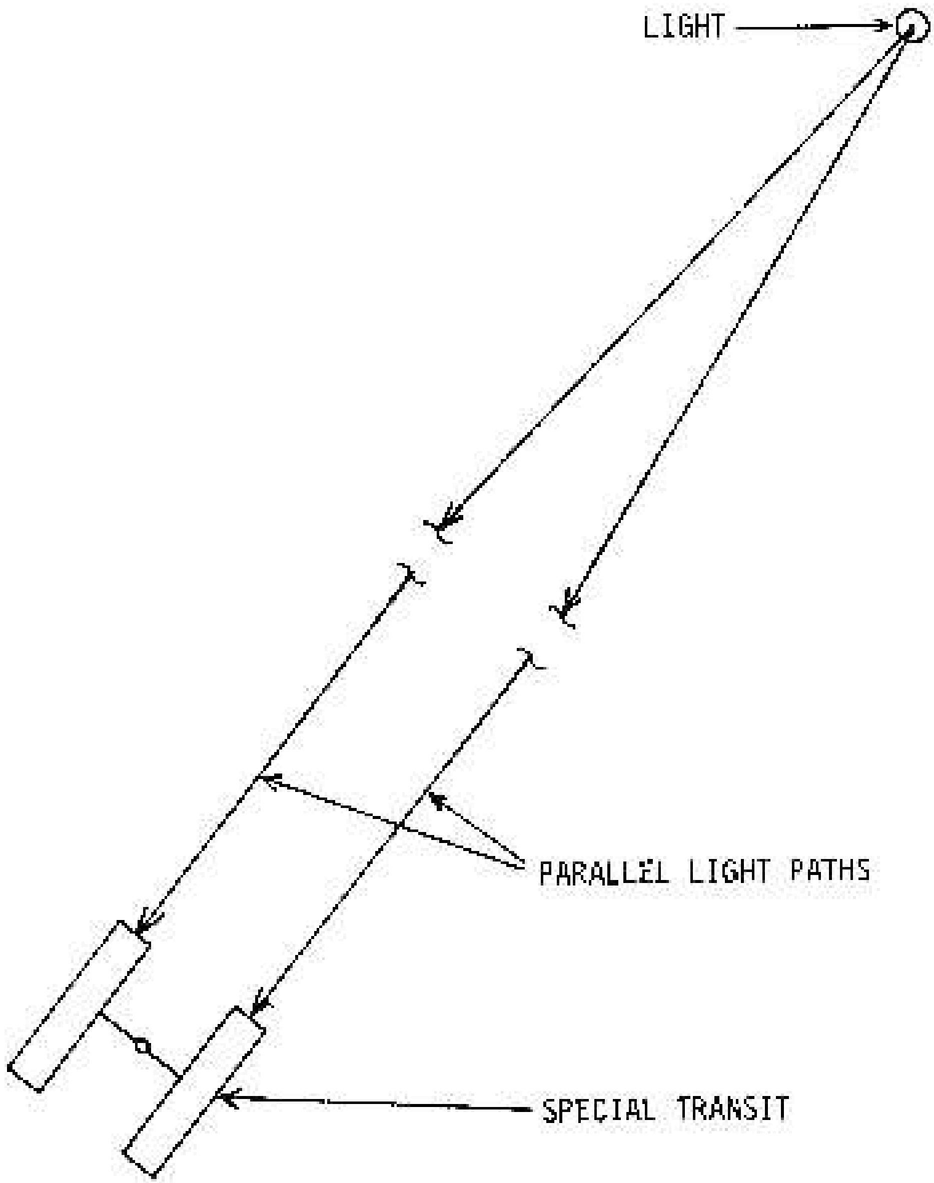


FIGURE 3.6 CONVERGENCE OF A DISTANT LIGHT

Most virtual image display systems do not produce perfect collimation. Instead the image will appear to be emanating from a shorter distance. For example, say centering a displayed point with both scopes results in an inward tilt of 4 mrad (see **Figure 3.7**). Geometric considerations show that the collimation distance is 35 mm/tan(2 mrad), or 17,500 mm. This corresponds to 17.5 meters or 57.4 feet. Often the Diopter will be used to express collimation distance and is defined as the inverse of the distance as measured in meters. In this example, the point appears at 17.5 meters, or 0.057 Diopters.

Having completed an overview of the principal issues and parameters involved with display system design, the next step is to examine the display input devices available and discuss configurations capable of satisfying typical user requirements. It will be seen that each device has certain capabilities and limitations; hence, care must be exercised in matching the device with a requirement. By way of introduction, it is worthwhile to begin with an example that illustrates the thought processes going into display system design.

4.0 Example Of Single-Channel Display System

Assume a simulator is being designed for training pilots for take-offs and landings in full daylight. A single channel of CGI having a 36° vertical by 48° horizontal FOV is deemed adequate for the task. An IG producing raster-scan color imagery with resolution comparable to that of normal broadcast TV is being used. What display system should be implemented?

4.1 “Real Image With Monitor” Approach

One simplistic solution involves placing a TV monitor directly in front of the pilot trainee, as in **Figure 4.1**. This is a type of "real image" display since the pilot is looking at a surface con-taining a light-emitting focused image; i.e., the cathodoluminescent phosphor of the monitor's Cathode-Ray Tube (CRT). Since a full-color image is required, a color CRT monitor will be used. Experience with home TV provides sufficient proof that a daylight scene can be simulated. Concerning the FOV, one begins by assuming that the largest readily available monitor will be used; i.e., a 25-inch CRT having a 4:3 aspect ratio. The nomenclature here refers to a rectangular display device having a diagonal of 25 inches and a picture width:height ratio of 4:3. Horizontal and vertical picture dimensions are thus 20 inches and 15 inches, respectively. To satisfy the FOV specification, the monitor must be placed at a sufficiently close distance to the pilot. **Figure 4.2** illustrates the calculations needed to derive the maximum permissible viewing distance.

The Top View illustrates how a maximum eyepoint/CRT separation X is derived based on a screen width of 20 inches and a half-angle $\Theta/2$ greater than 24 degrees. X is shown to be less than 22.46 inches. In a similar manner, the Side View derives a maximum X value of 23.08 inches based on a screen height of 15 inches and a half-angle $\vartheta/2$ greater than 18°. Satisfying both requirements implies X less than 22.46 inches (say, 22 inches) which then yields a FOV of 48.9° horizontally by 37.7° vertically.

The preceding example illustrates a common occurance in display engineering: the design of a system which meets a specification but is not well suited for flight training. To begin with, viewing a CRT from such a short distance lends itself to eye fatigue. Secondly, the illusion of distance is being destroyed by strong accommodation and convergence cues telling the trainee that the imagery is nearby. Third, any head motion sideways will generate shift in the angular position of the image that is larger than that arising from a comparable real-world scene. And finally, a 25 inch CRT display may prove to be too large to incorporate into the simulator cockpit at a distance from the pilot of only 22 inches.

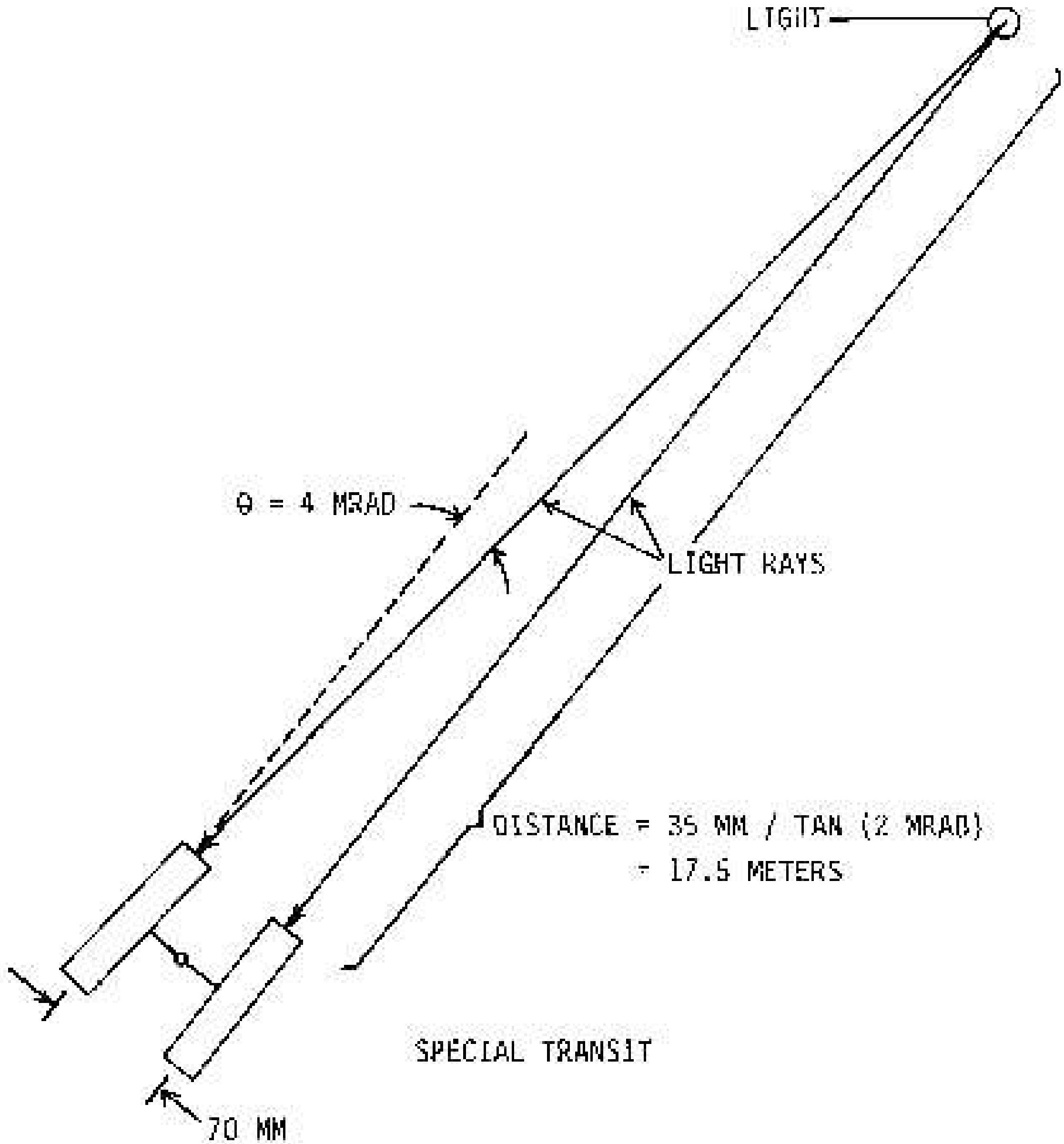


FIGURE 3.7 CONVERGENCE OF A NEARBY LIGHT

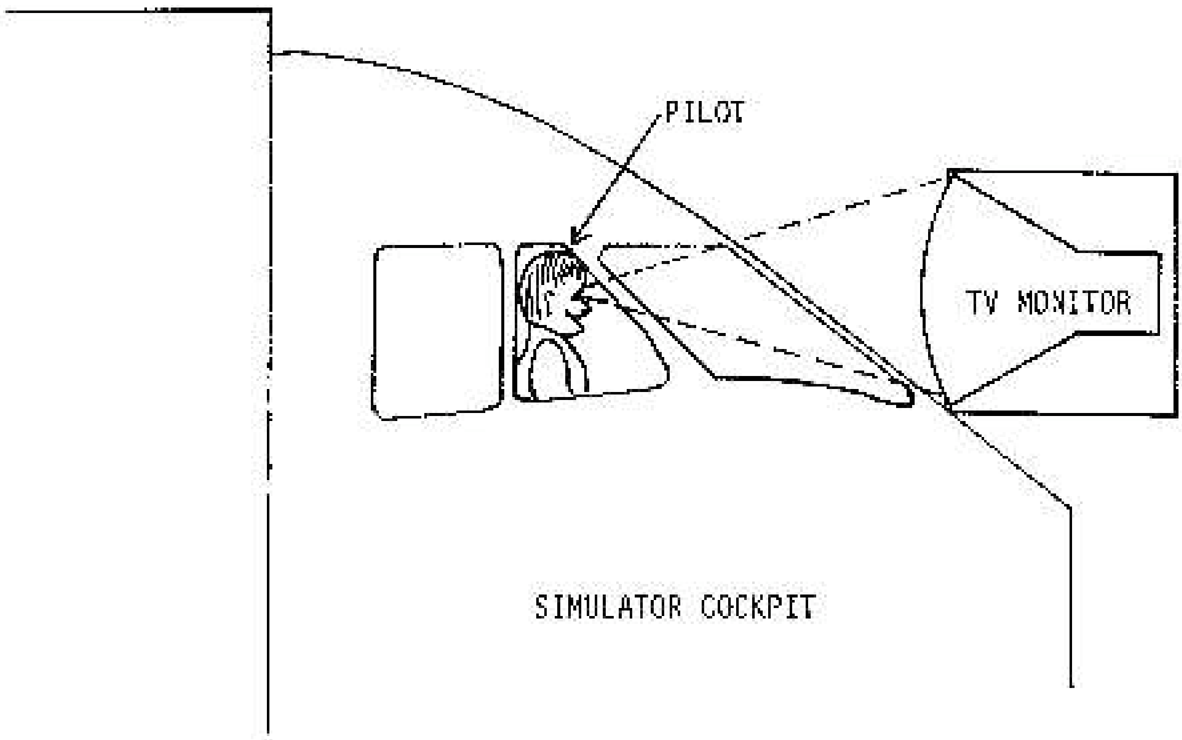
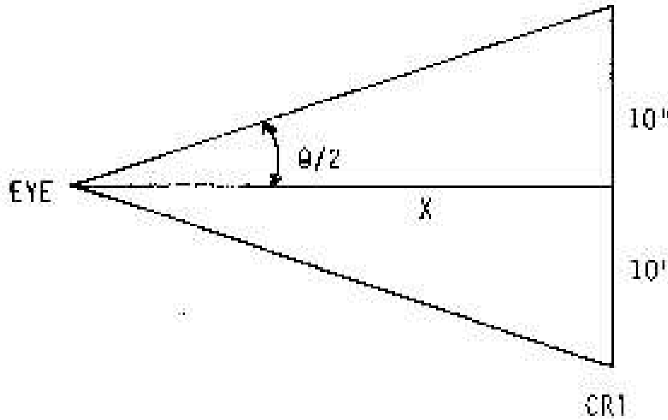


FIGURE 4.1 TV MONITOR DISPLAY



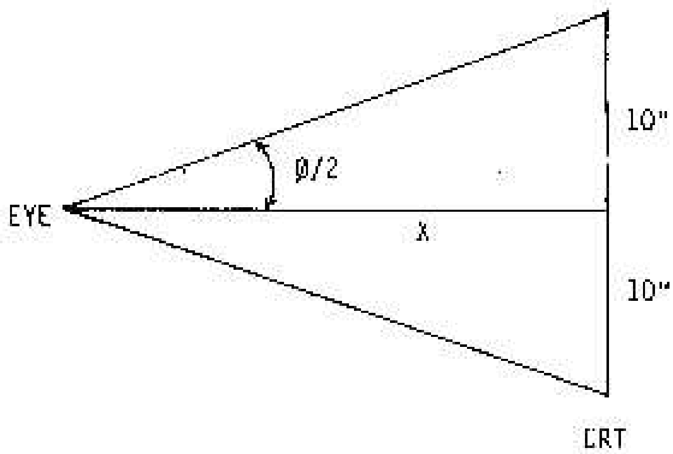
$\theta = 48^{o}$

TAN $(\theta/2) = 10/X$

$X = 10$ / TAN $(\theta/2)$ OR $X = 10$ / TAN 24^{o}

$X = 22.46$ INCHES

TOP VIEW



$\emptyset = 36^{o}$

TAN $(\emptyset/2) = 7.5/X$

$X = 7.5$ / TAN $(\emptyset/2)$ OR $X = 7.5$ / TAN 18^{o}

$X = 23.08$ INCHES

SIDE VIEW

FIGURE 4.2 CALCULATION TO DERIVE VIEWING DISTANCE OF MONITOR

4.2 "Real Image With Projector" Approach

It's worthwhile to re-examine this example and attempt to find a more elegant solution. One possibility is to use a video projector rather than the direct-view monitor. As illustrated in **Figure 4.3**, using the projector with a screen yields a focussed image; i.e., a "real" image that is viewable by the trainee. If we assume that the screen is a large but readily obtainable size such as 6 feet high by 8 feet wide, then the maximum pilot/screen separation X may be determined in a manner similar to the case of the direct view monitor. Here, the horizontal half-width of 4 feet implies X = 4/tan(24°) or X = 8.98 feet. The vertical half-width of 3 feet implies X = 3/tan(18°) or X = 9.23 feet. Satisfying both situations requires that X be less than or equal to roughly 9 feet. If 9 feet is chosen as the desired separation, then FOV will be 47.9° horizontally by 36.9° vertically. This is a compliant FOV assuming that the simulator buyer stipulates a reasonable tolerance of +1% on the FOV.

Before proceeding further with an analysis of the projection scheme, a comparison with the monitor solution is worthwhile since it shows three important benefits accruing to the latter. First, the greater eye relief (separation) is readily accommodated by the pilot's eyes. Secondly, there is ample room between the pilot and screen to permit the interposition of a cockpit structure. In fact, a Rediffusion simulator known as TRIAD having comparable geometry permitted the pilot to sit in an actual Bell 206 helicopter cockpit during the simulation exercise. Third and finally, lateral head motion will result in significantly less angular deviation of distant objects within the image, as illustrated in **Figure 4.4**. An object at a distance of one mile should appear nearly stationary if the head is moved sideways by 6 inches; i.e., its change in angular direction is about 100 microradians, or 0.005°. With the CRT monitor at 22 inches, a 6 inch head motion causes an angular change of roughly arctan(6"/22"), or 15.3°. The projection method, however, produces an angular change of only arctan(6"/108"), or 3.2°; i.e., (1/5)th the angular error of the monitor case.

Brightness considerations were passed over somewhat in the case of the direct-view display since 25-inch color CRTs are amply capable of producing imagery with brightness in excess of 50 ft.L. When projection is used, however, the available light output of three color CRT projection tubes must pass through an optical system (i.e. projection lens) of some f-number and subsequently be spread (magnified) over a large projection screen characterized by some value of screen gain. It is generally found that excess brightness is used for trading off brightness against brightness uniformity to achieve some optimum compromise in performance. The theory required for calculating this trade-off will be discussed in Section 5.0.

4.3 "Virtual Image With Monitor" Approach

Before leaving this example, one other display system to consider is a virtual image system, oftentimes called a collimated system. One manifestation of such a system involves placing the real image of a display input device in the back focal plane of a positive lens (see **Figure 4.5**). The lens serves to "collimate" the rays of light coming from the image (termed "object"); i.e., rays emanating from a given point in the image will always travel along parallel paths after passing through the lens, thereby forming a virtual image. As shown in the figure, one ray emanating from the top of the object is normally incident on the lens, after which it is directed through the front focal point of the lens, whereas the second ray passes straight through the center of the lens. Both rays end up travelling along parallel paths. The same is true of the two rays shown emanating from the object at the optical axis. In fact, parallelism results (approximately) for any set of rays emanating from a common point.

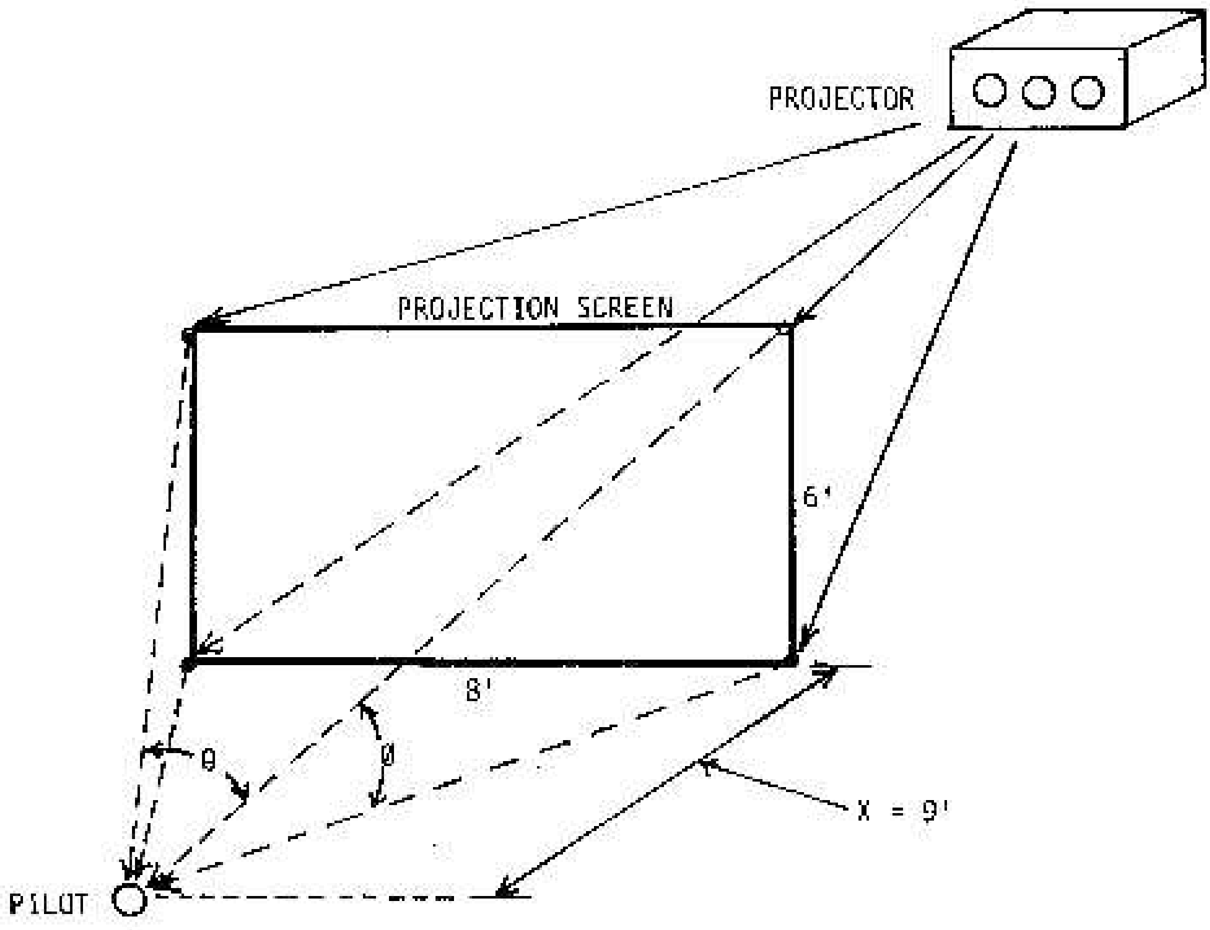


FIGURE 4.3 VIEWING DISTANCE WITH SCREEN DISPLAY

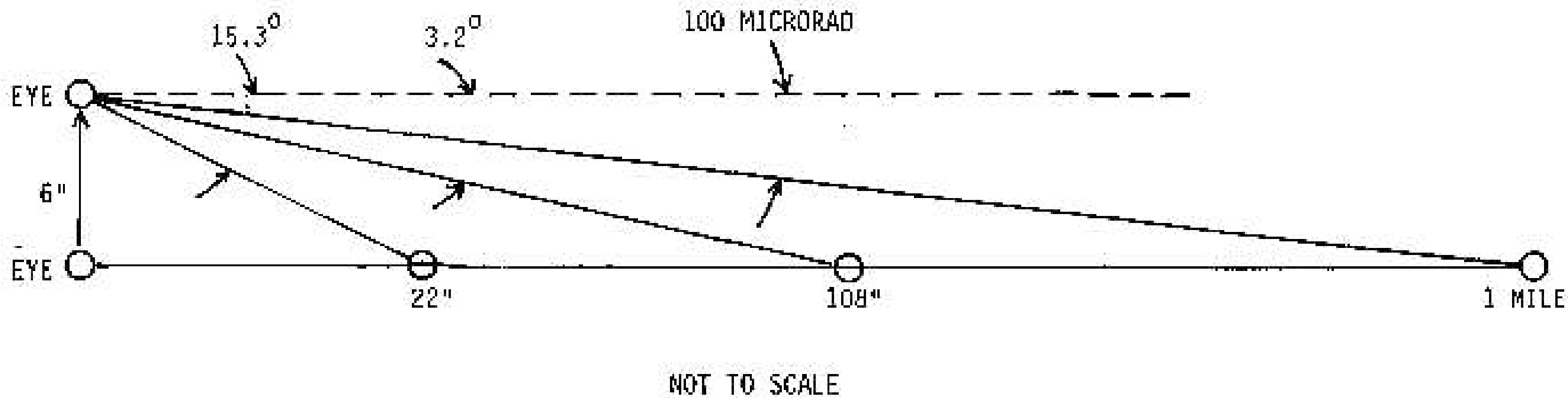


FIGURE 4.4 ANGULAR DEVIATION OF OBJECT WITH HEAD MOTION

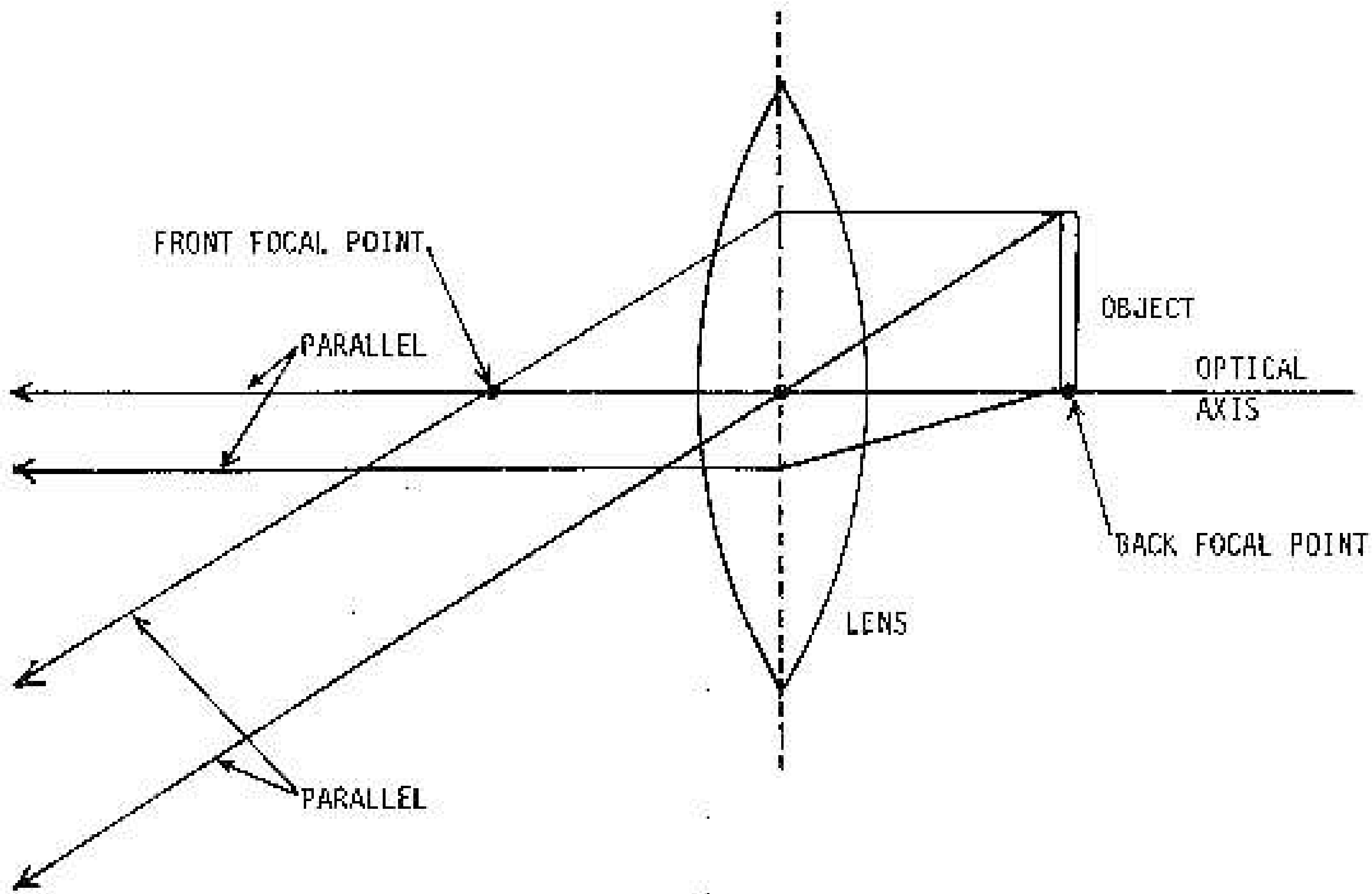


FIGURE 4.5 COLLIMATION WITH A LENS

This can also be shown mathematically using a formula that expresses the geometric relationship existing when a lens forms an image of an object that is arbitrarily located along the optical axis of the lens; i.e.,

$$(1/D1) + (1/D2) = (1/F)$$

where D1 is the object-lens distance, D2 is the image-lens distance, and F is the focal length of the lens. Solving for D2 yields

$$D2 = (F * D1)/(D1 - F)$$

If $D1>F$, then rays emanating from a point on the object will converge to form an inverted real image on the opposite side of the lens at a distance D2 from the lens (see **Figure 4.6**). If $D1<F$, then D2 is negative and rays emanating from a point on the object will diverge rather than converge on the other side of the lens. These diverging rays appear to emanate from a point located a distance D2 from the lens on the side containing the object; specifically, they appear to emanate from a "virtual" point located on an upright "virtual" image of the object (see **Figure 4.7**). However, if D1 = F. then D2 approaches infinity, implying that rays emanating from a point will pass through the lens and converge at an infinite distance from the lens. But this is simply the definition of parallelism in light rays, and parallelism is a characteristic of light rays arriving from a very distant source. Hence, one arrives at the interesting result that placing an object at the back focal plane of a positive lens will result in the object appearing to be distant when viewed through the lens.

Thus, consider the requirement for a 36° x 48° FOV. Using a 25-inch diagonal color CRT and a 25-inch focal length positive lens of comparable dimensions, the appropriate FOV may be generated as shown in **Figure 4.8**. Representative ray traces illustrate that the required FOV is obtained if the CRT is viewed through the lens from a point closer than 25 inches in front of the lens. Generally a larger viewing volume is needed; this is accommodated by using a larger diameter lens as shown in **Figure 4.9**.

Manufacturing a solid glass lens 25 inches or larger in diameter is both difficult and costly, especially if the f-number is one or less. In addition, color dispersion is a problem owing to the three primary colors (red, green, and blue) being refracted differently by the single glass lens. More complicated lens systems can alleviate this problem, but the difficulty and cost of manu-facturing them is proportional to the number of elements involved and thus precludes their consideration in most commercial systems.

One solution to this problem, which is used not only in flight simulation but other areas (e.g. Astronomy) as well, is to replace the refractive optics (lenses) with reflective optics (mirrors). Two possible configurations are illustrated in **Figures 4.10** and **4.11**. The former one incorporates a beamsplitter to produce an on-axis system with a folded optical path. The latter one has no beamsplitter; geometric constraints require that the components be off-axis to permit viewing of a virtual image.

The key to this reflective approach rests with the fact that a concave mirror having a radius R will have an effective focal length of R/2. Put another way, one can simulate (to first-order) the light-focusing properties of a lens having positive focal length F using a concave mirror having a radius of curvature equal to 2F. In this example, using a mirror of radius R = 50 inches provides the needed 36° by 48° FOV at distances from the mirror of less than R.

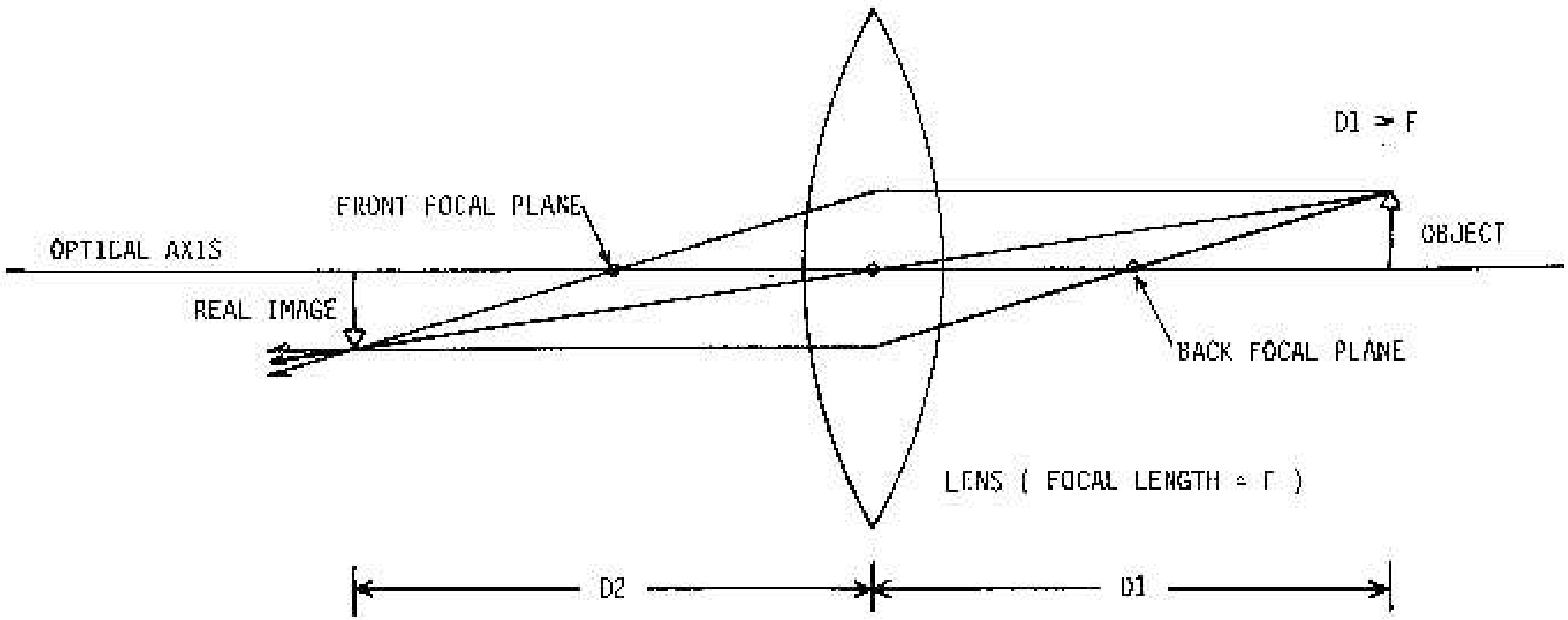


FIGURE 4.6 FORMATION OF A REAL IMAGE

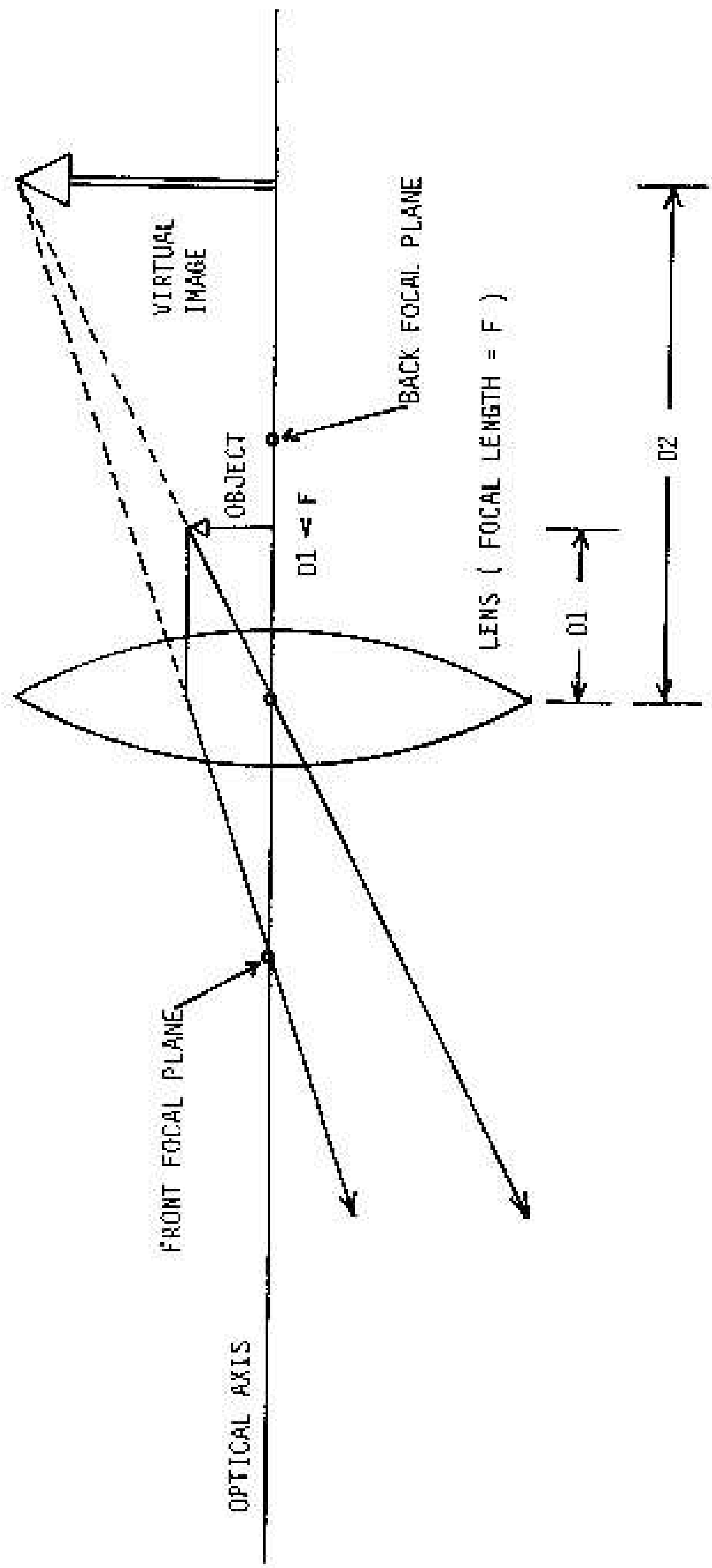


FIGURE 4.7 FORMATION OF A VIRTUAL IMAGE

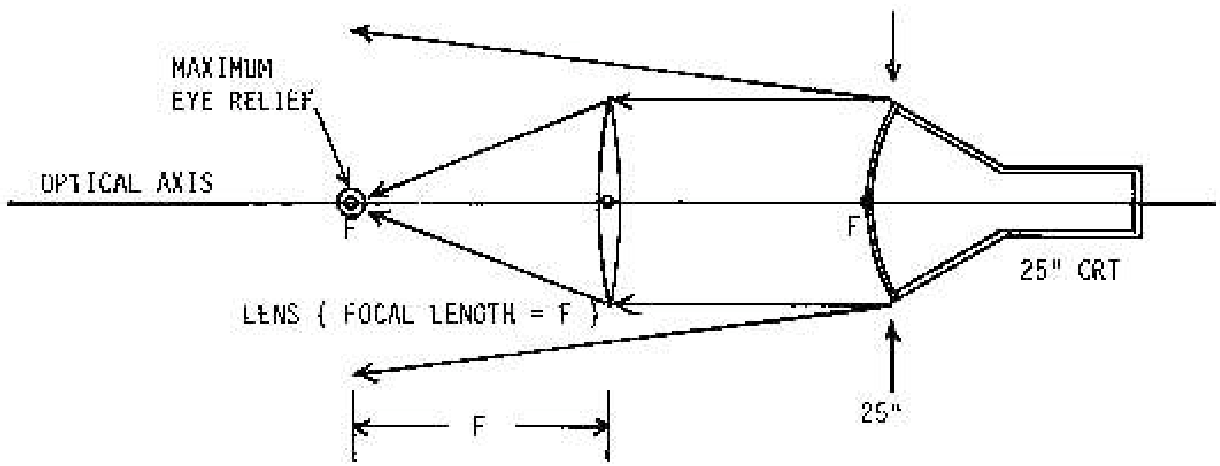


FIGURE 4.B   COLLIMATION WITH SMALL LENS

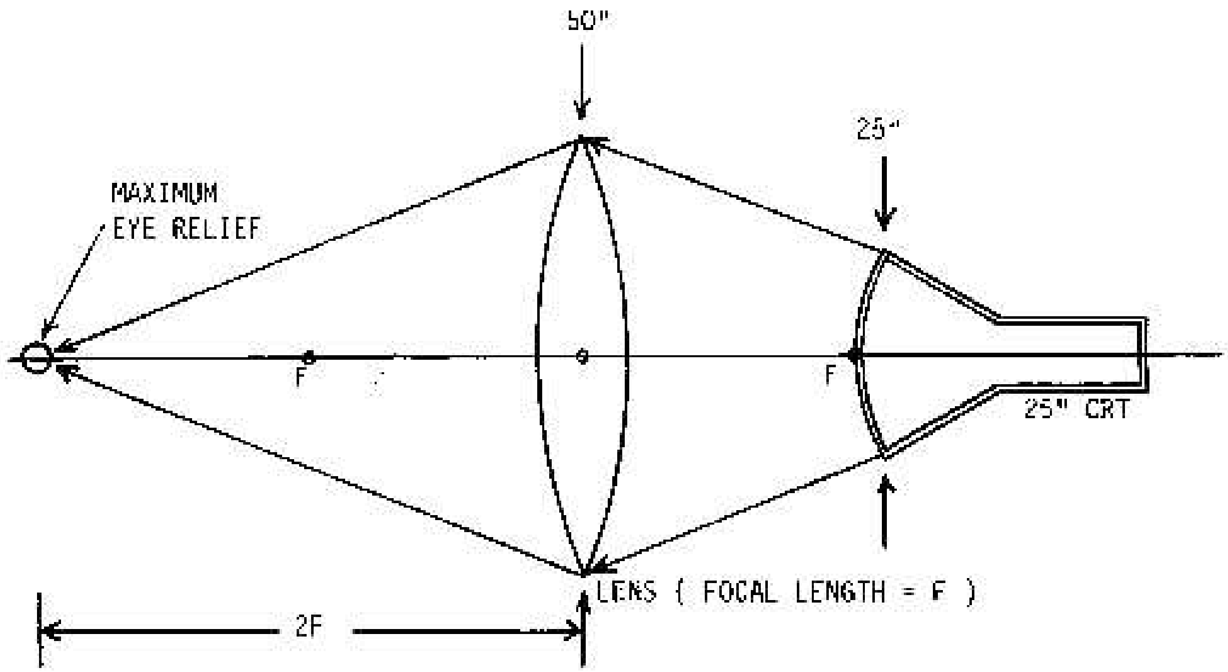


FIGURE 4.9 COLLIMATION WITH LARGE LENS

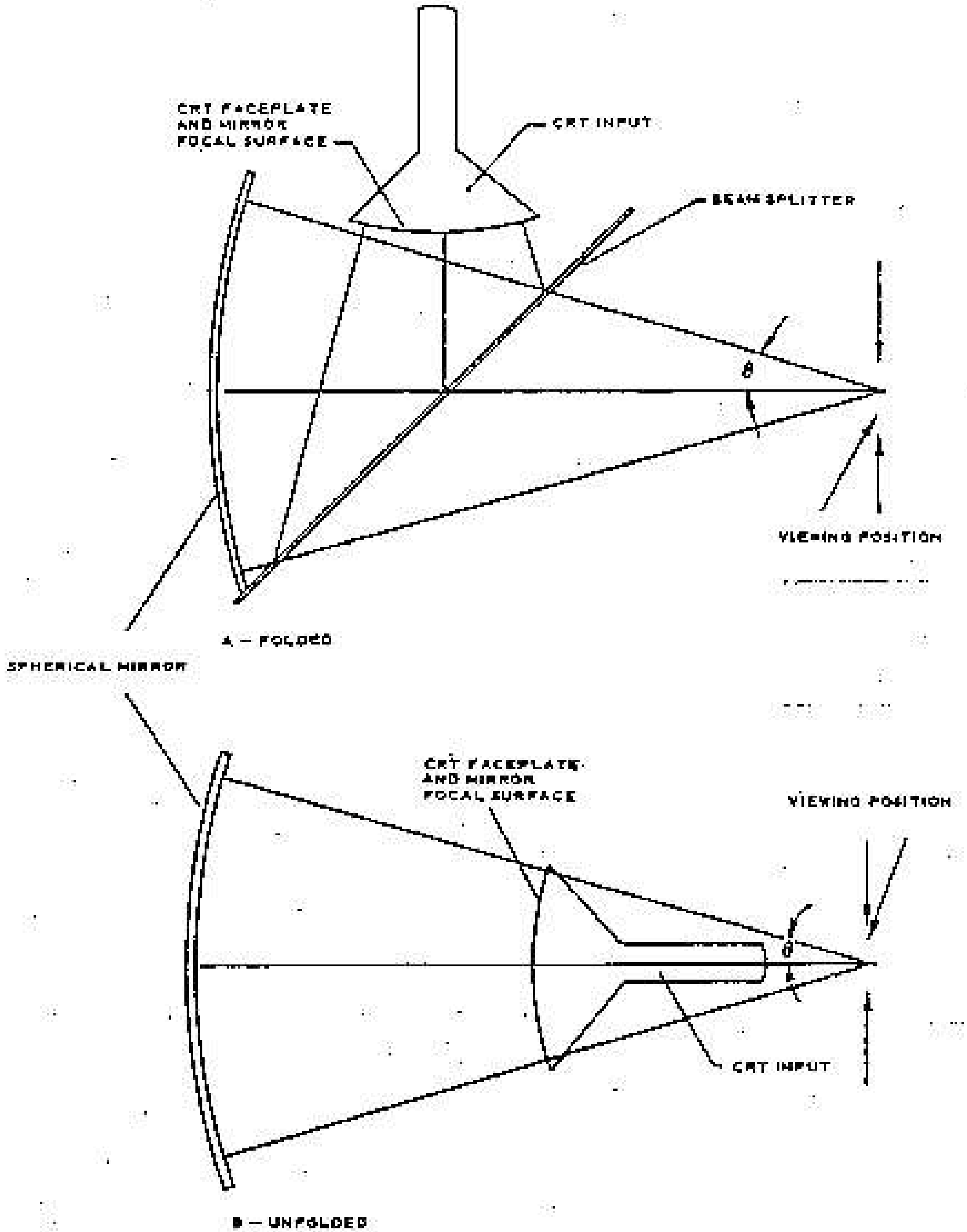


FIGURE 4.10 FOLDED BEAMSPLITTER/MIRROR SYSTEM

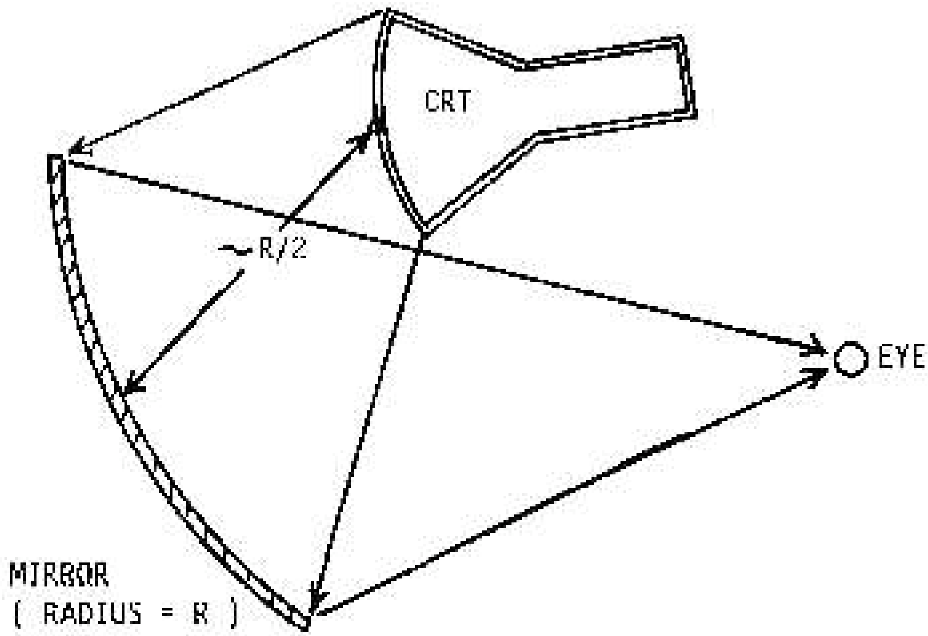


FIGURE 4.11 OFF-AXIS MIRROR SYSTEM

It should be noted that packaging constraints imposed by mirrors can limit the FOV attainable. In the case of a 36°by 48° FOV, a 50-inch radius mirror requires that the CRT must be 25 inches from mirror center, yet not occult the image. In the case of the folded mirror system, the 7–1/2 inch half-height of the CRT implies that a mirror having a half-height of 17–1/2 inches may be used. Such a mirror will produce the specified FOV up to a distance of 54 inches from the mirror. However, a larger FOV using the same 25-inch CRT would need a shorter focal length mirror. Since the CRT would have to be positioned closer to the mirror, the 17–1/2 inch half-height of the mirror would need reducing since the 7–1/2 inch portion in front of the mirror is fixed by the CRT size. For example, if a 48° vertical by 64° horizontal FOV was required using a 25-inch CRT, then the needed lens or mirror focal length is determined by computing the minimum focal length set by the required horizontal and vertical FOVs:

Horizontal: 10"/tan(32°) = 16 inches
Vertical: 7.5"/tan(24°) = 16.85 inches

Using a mirror of radius R = 32 inches (or F = 16 inches), mirror half-height can be only 8–1/2 inches. This yields a full 48° vertical FOV when viewed from a distance no greater than 19 inches from the mirror. This just about places the pilot trainee's head directly against the beamsplitter and will probably prove unacceptable. The same principles hold for the off-axis mirror system since decreasing focal length forces the CRT closer to the mirror, thus tending to limit vertical FOV. In contrast, the in-line lens system has no such problem. Using a 16-inch focal length lens of 25-inch diameter allows the pilot to be up to 16 inches from the lens with no intervening beamsplitters getting in the way. If a greater viewing distance is needed, then a larger lens can be used without the worry of interference coming from the CRT.

Leaving FOV and considering the remaining optical parameters, it is apparent that the performance of the three virtual image displays is not identical. The lens systems of **Figures 4.8** and **4.9** will produce Fresnel losses in brightness at each surface of the lens; however, these may be kept to a few percent by anti-reflection (AR) coating both lens surfaces.

The folded mirror system of **Figure 4.10** will have two sources of attenuation: mirror and beamsplitter. The mirror has a reflectivity r less than 1; if r = 0.8, then 20% of the light is lost by the mirror. The beamsplitter nominally transmits and reflects equal amounts of light—termed a 50/50 beamsplitter. Since this system only utilizes that portion of light reflected and then transmitted, an amount is lost corresponding to light which is transmitted on the way to the mirror and reflected back from the mirror. Quantitatively, 50% of the light reaches the mirror, and 50% of the reflected light reaches the pilot. Hence, the beamsplitter is only 25% efficient and accounts for a 75% loss of light. In this example for which r = 0.8, the overall transmission of the folded mirror system is 0.5 x 0.8 x 0.5 equals 0.2, or only 20% of the initial brightness reaches the eyepoint.

The off-axis mirror system of **Figure 4.11** will have a brightness that is solely dependent on mirror reflectivity. If r = 0.8, then 80% of the brightness will be available to the pilot trainee, or 4x that available with the folded mirror design.

Lest one conclude that the folded mirror design is the least desirable of the three systems, mention should be made of color convergence, collimation, geometry, and cost. Given perfect convergence at the CRT faceplate, components such as front-surface mirrors and beamsplitters will have a negligable effect on color convergence. A single glass lens, however, will tend to bend red, green, and blue light rays by different amounts and thereby worsen convergence. The solution, to use a doublet or triplet lens, further increases the cost of an already relatively expensive system since grinding and polishing the two surfaces of a large piece of high-quality glass is much more complicated than a comparable set of operations on the single surface of a glass or metallic mirror.

In the simple systems addressed here, collimation is optimized when the CRT face is a distance F = R/2 from the lens or mirror. In addition, the CRT face (or screen if projection is used) should have a radius of curvature roughly equal to F/2 = R/4. Most 25-inch color CRTs have a faceplate radius of about 40 inches—too large for a 50-inch radius mirror. If the center of the CRT face is properly positioned for collimation, then the observer's eyes will need to converge slightly to view portions of the image off-axis, corresponding to a collimation distance less than infinite. This problem is not too severe in a lens or folded mirror system since the collimation distance never gets below about 30 feet and, additionally, any errors are circularly symmetric. In the off-axis system, however, the top and bottom of the CRT face tend to be different distances from the mirror; the top generally being closer. The result is a worst-case collimation distance that is nearer than that achievable with an on-axis or folded system since guaranteeing light divergence or parallelism at the top of the CRT face will force the middle and bottom to be disproportionately far from the mirror.

Geometry is another area in which the off-axis system is at a disadvantage. The CRT tends to have barrel distortion when viewed directly, owing to the convex curvature of the faceplate. The on-axis lens and folded mirror system introduces slight pincushion which partly cancels this distortion. Additional pincushion correction can be introduced electronically, resulting in near-perfect image geometry. The off-axis system, however, must compensate not only for barrel distortion of the CRT but for keystone—trapezoidal—distortion arising from the tilted arrangement of the components. The picture at the CRT face will typically need to appear as in **Figure 4.12**, with the top expanded in width and the bottom contracted. Even assuming the display device is capable of introducing this predistortion, secondary issues involving brightness uniformity and resolution arise. Because the top portion of the image involves more phosphor than the bottom portion, the image will be brightest at the top, gradually decreasing towards the bottom. Similarly, resolution will be better at the top since the picture information is more spread out at the top; hence, the resolution limit of the display becomes less of a factor in overall image resolution.

5.0 Display Input Devices

The display input device, as defined here, is a transducer that converts electrical signals originating in the IG into a two-dimensional luminous image. The previous example touched on two such devices: the CRT monitor and CRT projector. Beginning with the CRT monitor, this section attempts to provide a basic understanding of the physical principles involved in the display input device so an appreciation of the devices capabilities and limitations may be obtained.

5.1 Monochrome CRT's

Figure 5.1 shows schematically the elements comprising a monochrome (single color) CRT. A heated cathode C emits a stream of electrons that is accelerated in stages to a faceplate containing phosphor. The control grid G1, being closest to the cathode, determines the field at the cathode surface and the amount of current drawn. Phosphor emission is proportional to the number of electrons; thus, G1 controls spot intensity at the faceplate by regulating beam current. The screen grid G2, in conjunction with the control grid, forms an electrostatic lens that produces an electron image of the cathode surface at the plane P2. A plane P1 also exists in front of the screen grid. Here, the electron beam has its minimum cross-sectional diameter—termed the crossover point. Two additional anodes, A1 and A2, impart additional acceleration to the electrons and also form an electrostatic lens that tightly focuses the electron beam onto the phosphor, usually by imaging the crossover point. Because the focussing is accomplished using specially shaped metal plates to apply electrostatic forces, the tube is said to have "electrostatic focus". The two coils shown in the figure produce orthogonal, lateral magnetic fields which deflect the beam horizontally and vertically, permitting the whole faceplate to be addressed. Such a deflection scheme, based on magnetic forces, is termed "magnetic deflection".

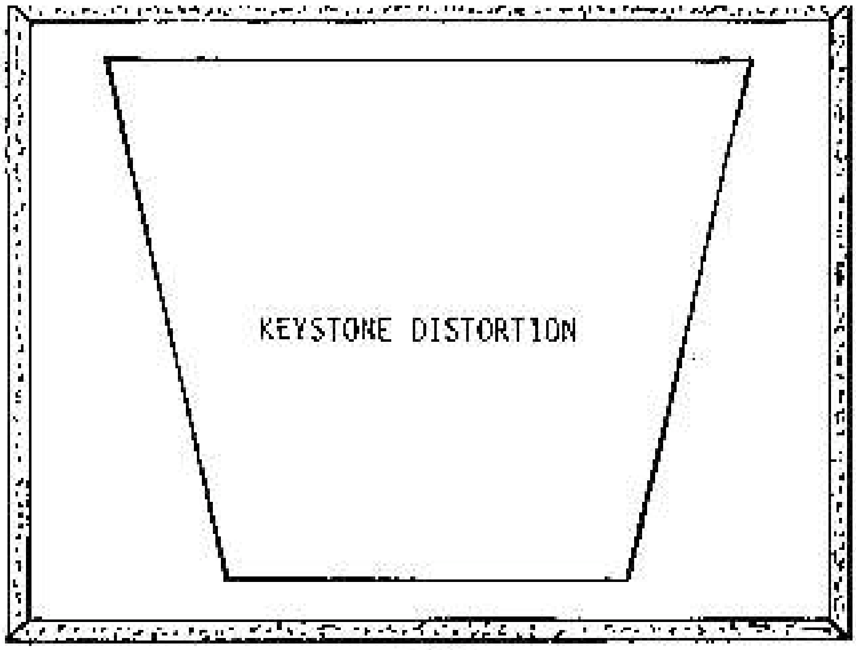


FIGURE 4.12 KEYSTONE CORRECTION NEEDED FOR OFF-AXIS SYSTEM

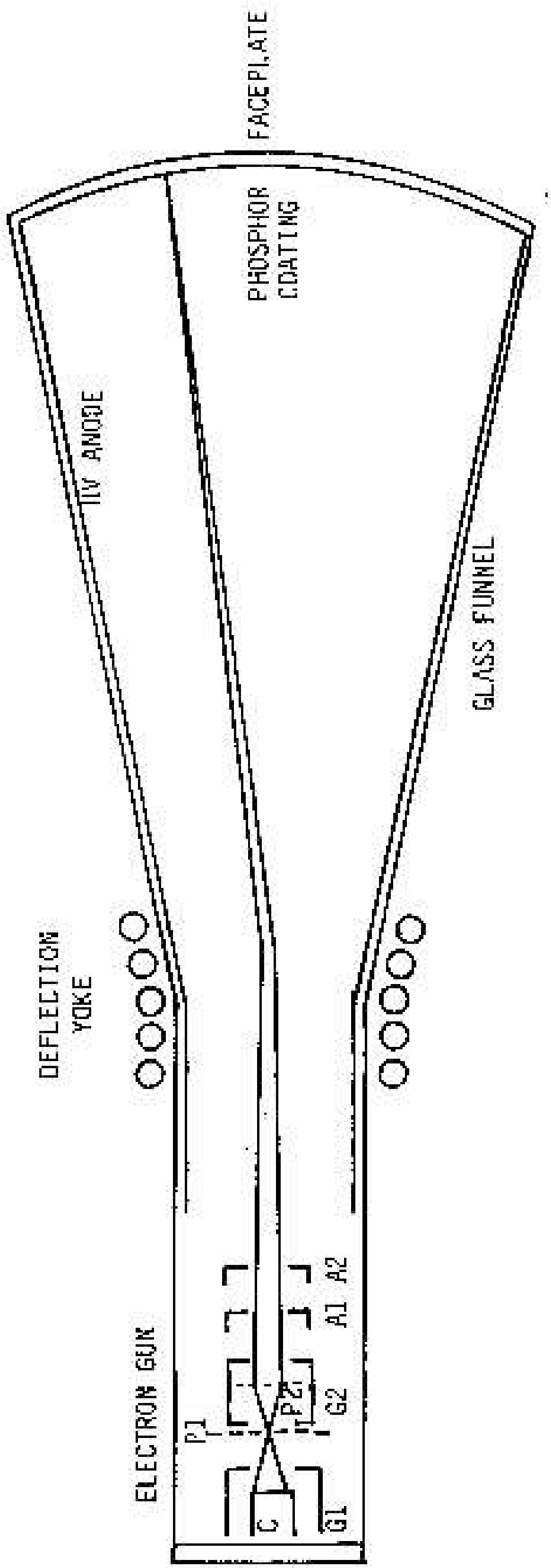


FIGURE 5.1 MONOCHROME CRT

CRT's may also be constructed which incorporate magnetic focus and/or electrostatic deflection. Good, uniform spot sizes can be obtained with either electrostatic or magnetic focus. However, if rapid defocus capability is needed to support perspective growth of individually displayed lights or some similar special effect, then magnetic focus has an advantage owing to the difficulty of rapidly driving the capacitive loads inherent with electrostatic focus. Concerning deflection, magnetic causes less spot defocus with deflection angle and is thus preferred when large deflection angles are involved and power consumption is not a critical issue.

The luminous CRT image is formed in a phosphor that is deposited on a flat, concave, or convex faceplate of good optical quality. A thin conducting layer of aluminum is often applied to the back surface of the phosphor to prevent charge build-up at the faceplate. Such an "aluminized" faceplate also has the benefit that it reflects light to the viewer that would normally be trapped in the tube funnel, thus making for a brighter image with improved contrast.

There exist a multitude of phosphors; these are simply inorganic crystalline materials containing specific impurities (activators) which, in conjunction with the host crystals, promote luminescence. A phosphor can be classified according to three parameters that depend on the chemical and physical properties of the phosphor; these are spectral emission, persistence, and luminous efficiency. Spectral emission relates to the color of the emitted light and determines whether the phosphor is red, green, blue, white, or whatever. Persistence is a measure of how long and to what degree the phosphor emits light after being excited by the electron beam. Long persistence generally makes for a brighter image with less flicker; however, rapidly moving displayed objects tend to smear, resulting in an objectionable image artifact known as "tailing". Because dynamic imagery is the norm in flight simulation, phosphors having medium or short persistence are usually used. Efficiency is a measure of the amount of light output relative to the amount of electrical power provided and is usually measured in lumens/Watt. An efficiency value greater than 5 is usual for CRT displays. **Figure 5.2** illustrates the spectral emission of a common green phosphor known as P1. The persistence characteristic for P1 is shown by the curve of **Figure 5.3**. A traditional scalar measure of persistence is the time until brightness has dropped to 10% of its initial value. P1, for example, has a value of 24.5 msec and is said to have "medium" persistence.

5.2 Beam-Penetration CRTs

The CRT described thus far is suitable for providing a single color display. Though adequate in many applications, full color is the norm in flight simulation and requires a more elaborate CRT. One solution is to use a beam-penetration phosphor such as P50 or P51. These phosphors incorporate a red and green component which are traditionally deposited in two layers onto the faceplate, as shown in **Figure 5.4**. Alternatively, the green phosphor particles are coated with the red phosphor and then applied; this is termed an "onionskin" phosphor. Regardless of the fabrication technique employed, the end result is a phosphor with a spectral emission that varies with the anode voltage of the tube. For example, P50 is a phosphor meant to operate between 8kV and 15kV. At 8kV the red component is favored and the emitted light is a fairly saturated red of about 6075 Angstroms. At 15kV the green component is favored and the emitted light is a yellow-green having a center wavelength of roughly 5650 Angstroms. Voltages in between can be used to generate orange, amber, and yellow-white. **Figure 5.5** illustrates the voltage-dependent emission with a Kelly Chart. The straight line has its ends in the red and yellow-green, corresponding to 8kV and 15kV, respectively. Any color lying on a line between these two points is achievable through proper selection of anode voltage. It should be noted that the color blue is not readily obtainable with a beam-penetration phosphor; however, phosphor manufacturers are currently attempting to develop a beam penetration phosphor which will have a blue component.

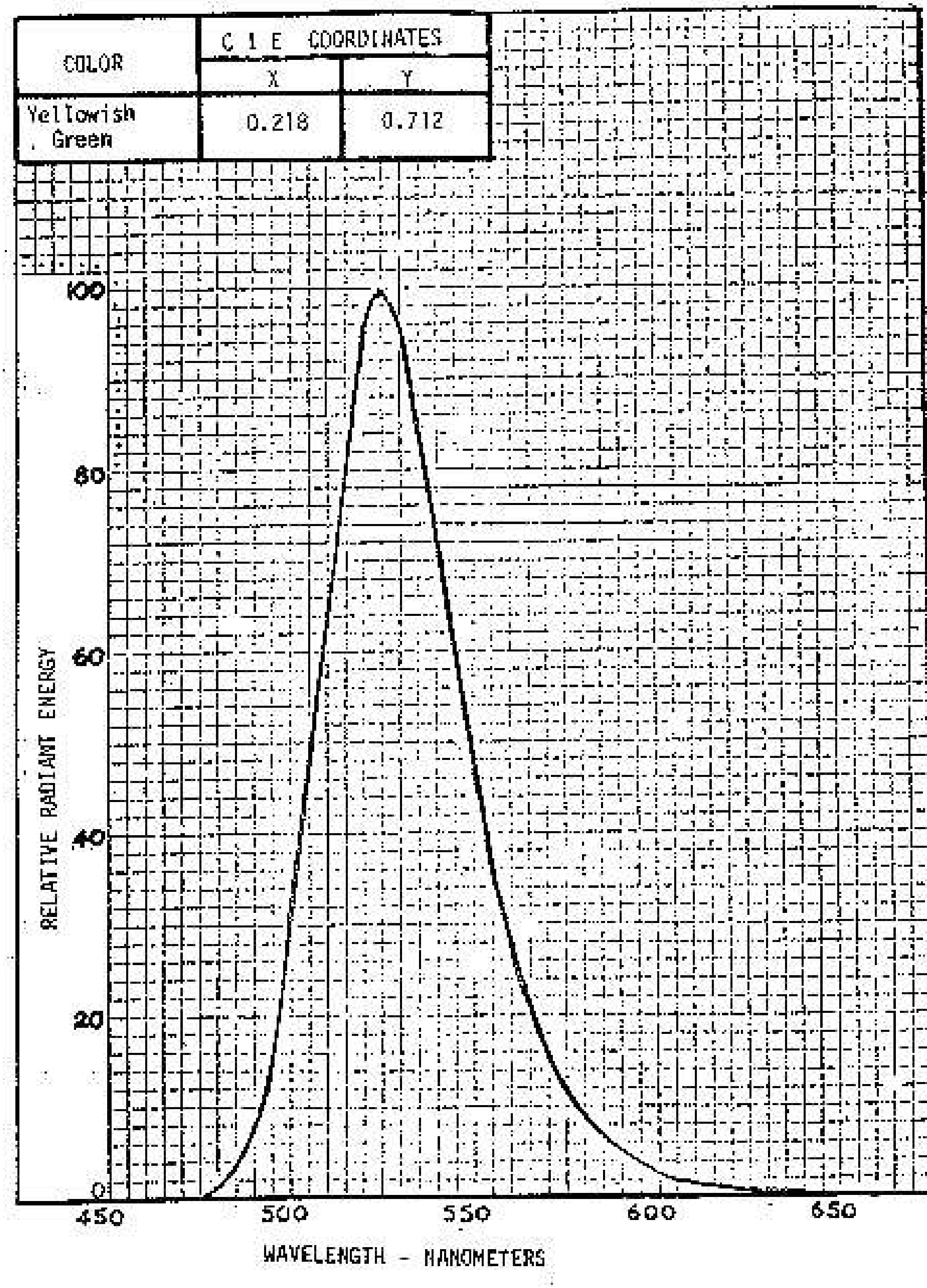


FIGURE 5.2 SPECTRAL EMISSION OF PHOSPHOR P1

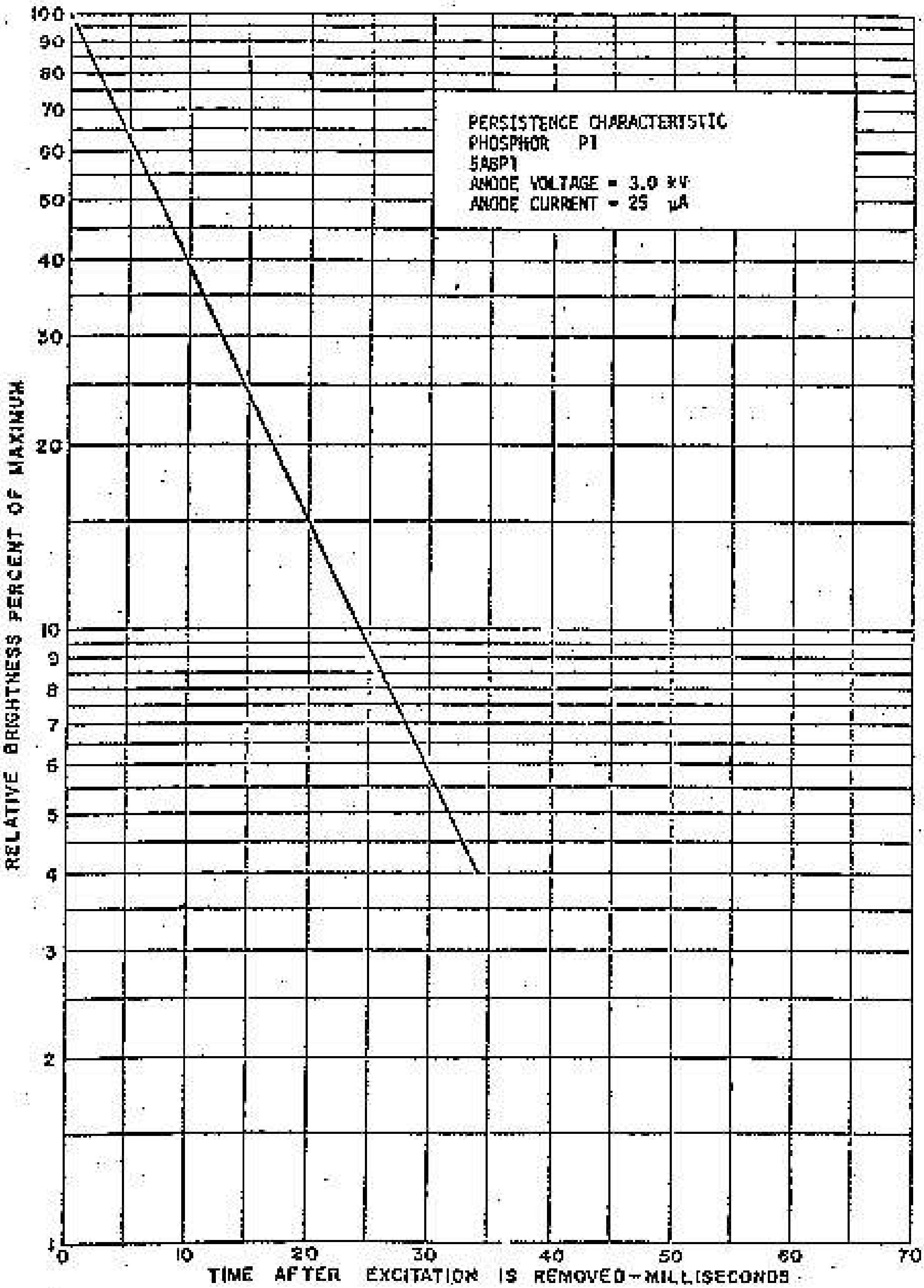


FIGURE 5.3 PERSISTENCE CHARACTERISTIC OF PHOSPHOR P1

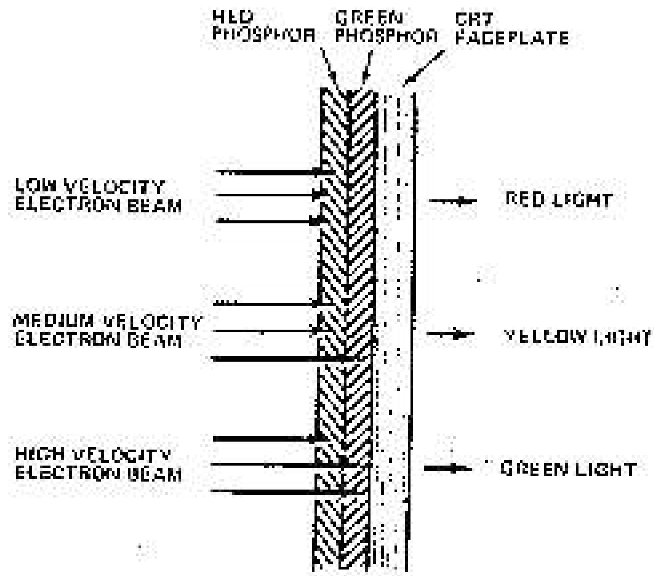


FIGURE 5.4 LAYERED PHOSPHOR FOR "BEAM PENETRATION" TUBE

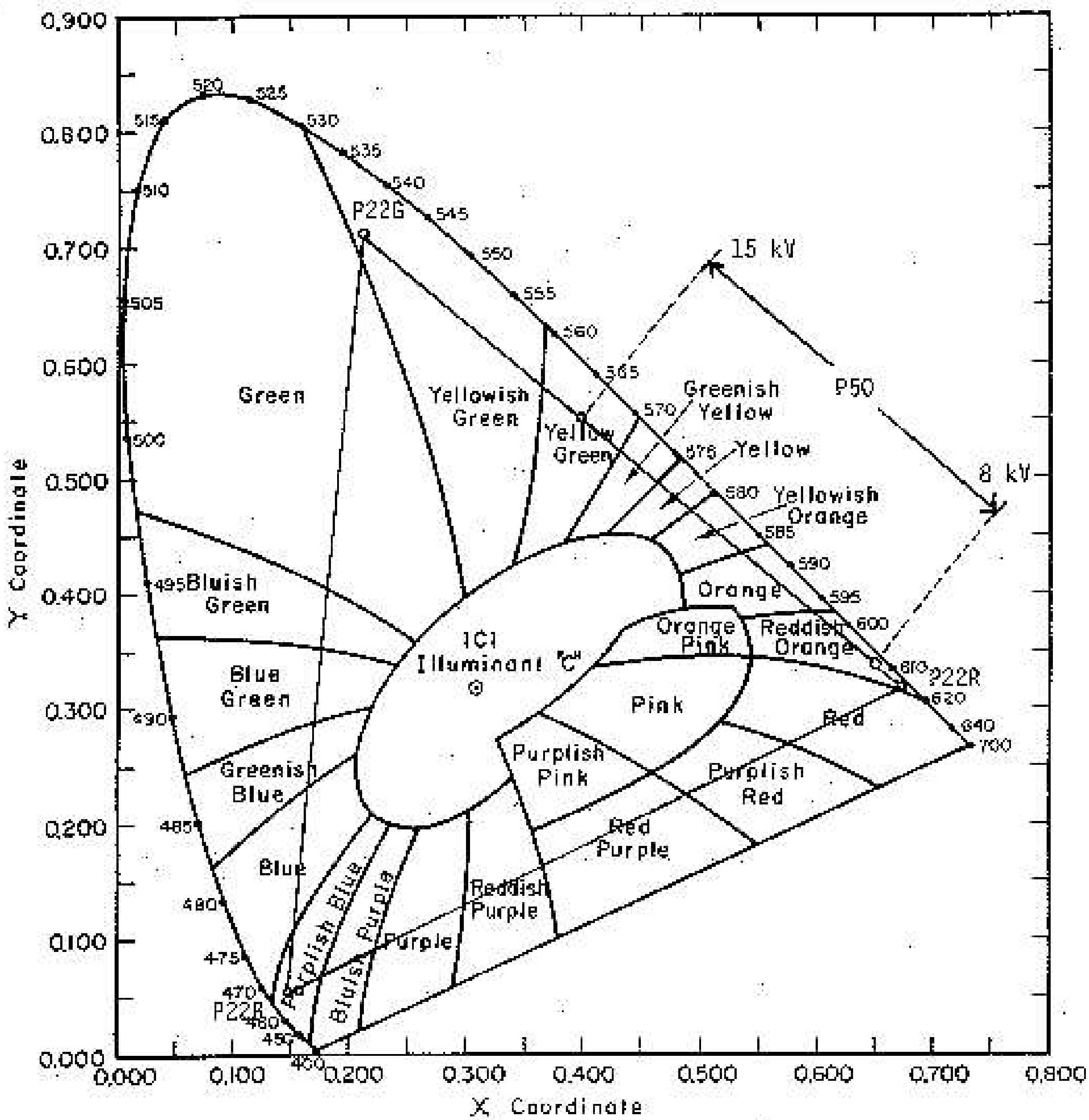


FIGURE 5.5 KELLY CHART SHOWING P50 AND P22R, G, B

5.3 Full-Color CRT Projectors

Strictly speaking, to achieve full-color by industry standards requires that three phosphors be used: red, green, and blue. The Kelly Chart in **Figure 5.5** shows the coordinate locations for the P22 R, G, and B phosphors used in commercial TV. The triangular area enclosed by these points defines the range of colors obtained by varying the intensity of each phosphor component. Note that a true white (denoted by CIE Source C), is attainable with a 3-color system but not with the beam-penetration system utilizing two colors.

The easiest way of achieving full-color is to use a projection system having three CRT's. Each tube has a phosphor of a primary color and is oriented to produce an overlapping image at the projection screen. Color projectors having 40" or 50" diagonal screens are common these days for consumer use, and larger screen sizes are possible using more powerful commercial-grade projectors. A multitude of companies produce full-color projectors, but only a few have found application in flight simulation. Some of these will be discussed in the following.

Figure 5.6 shows a configuration for a Cessna 421 simulator that uses three adjacent, concave, front-projection screens. The three raster-scan projectors are Aquastar III C projectors built by ESP, Inc. of Titusville, Florida. The Aquastar contains three projection tubes having P22 R, G, and B phosphors that are arranged in a linear side-by-side manner. The projectors sit above and behind the aircraft cab, illuminating the screens with a cross-fire geometry. The surface of the screens are roughly perpendicular to the pilot's line-of-sight. Three separate screens are employed, so gaps exist in the field-of-view defined by the visual. However, since the imagery is generally quite dynamic, objects do not dwell in the gaps very long and thus the quality of the visual presentation does not suffer too much.

Resolution of the Aquastar is specified as 1000 TV lines. If one assumes an IG producing 1000 lines by 1333 pixels/line with a FOV of 36° vertical by 48° horizontal, then a resolution per pixel of 36° ÷ 1000 lines, or 2.16 arc-minutes per pixel, is expected. This is only approximately true, however, and is based on the fact that the IG nominally computes a planar image with uniform resolution; i.e., uniform pixel density. **Figure 5.7** illustrates the principle involved by considering the angular size of pixels in the vertical direction at screen center. At screen center,

$$\Theta CTRV = \arctan\left[(2/\#LINES)\tan(\Theta HLF)\right]$$

Since #LINES = 1000 and ΘHLF = 18°, CTR = 2.23 arc-minutes which is 3% larger than the value obtained by simply dividing the angle by the number of pixels. **Figure 5.8** illustrates the derivation for ΦEDG , the angular subtense of a pixel at the screen edge. The angle ΦEDG is expressed as:

$$\Phi EDGV = \Theta HLF - \arctan\left[((\#LINES/2)-1)(2/\#LINES)\tan(\Theta HLF)\right]$$

Since ΘHLF = 18° and #LINES = 1000 as before, ΦEDG = 2.02 arc-minutes which is 6% smaller than the nominal value of 2.16 arc minutes. Similar derivations can be performed in the horizontal direction to yield:

ΦCTRH = 2.3 arc-minutes/pixel (6% larger)
ΦEDGH = 1.92 arc-minutes/pixel (11% smaller)

TOP VIEW

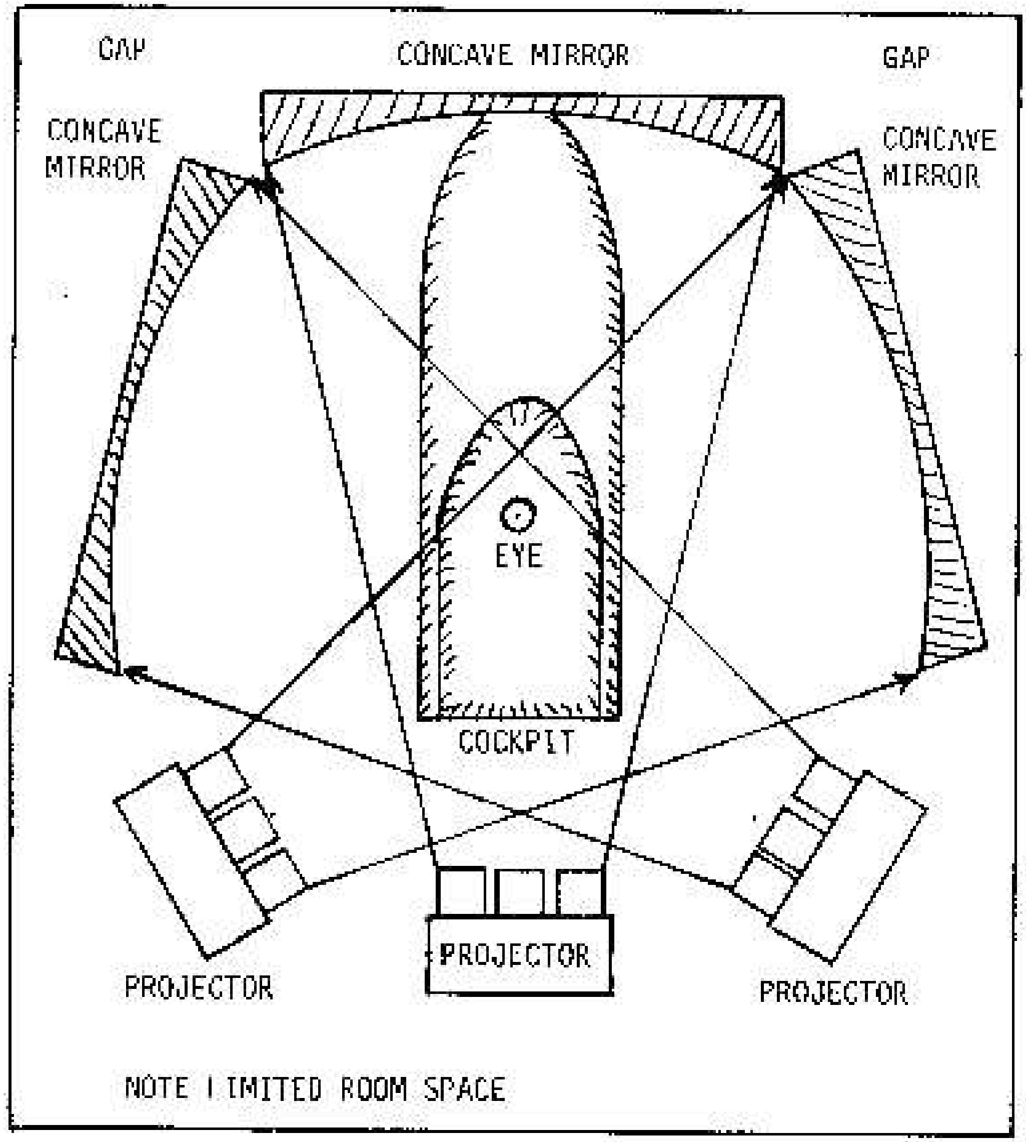
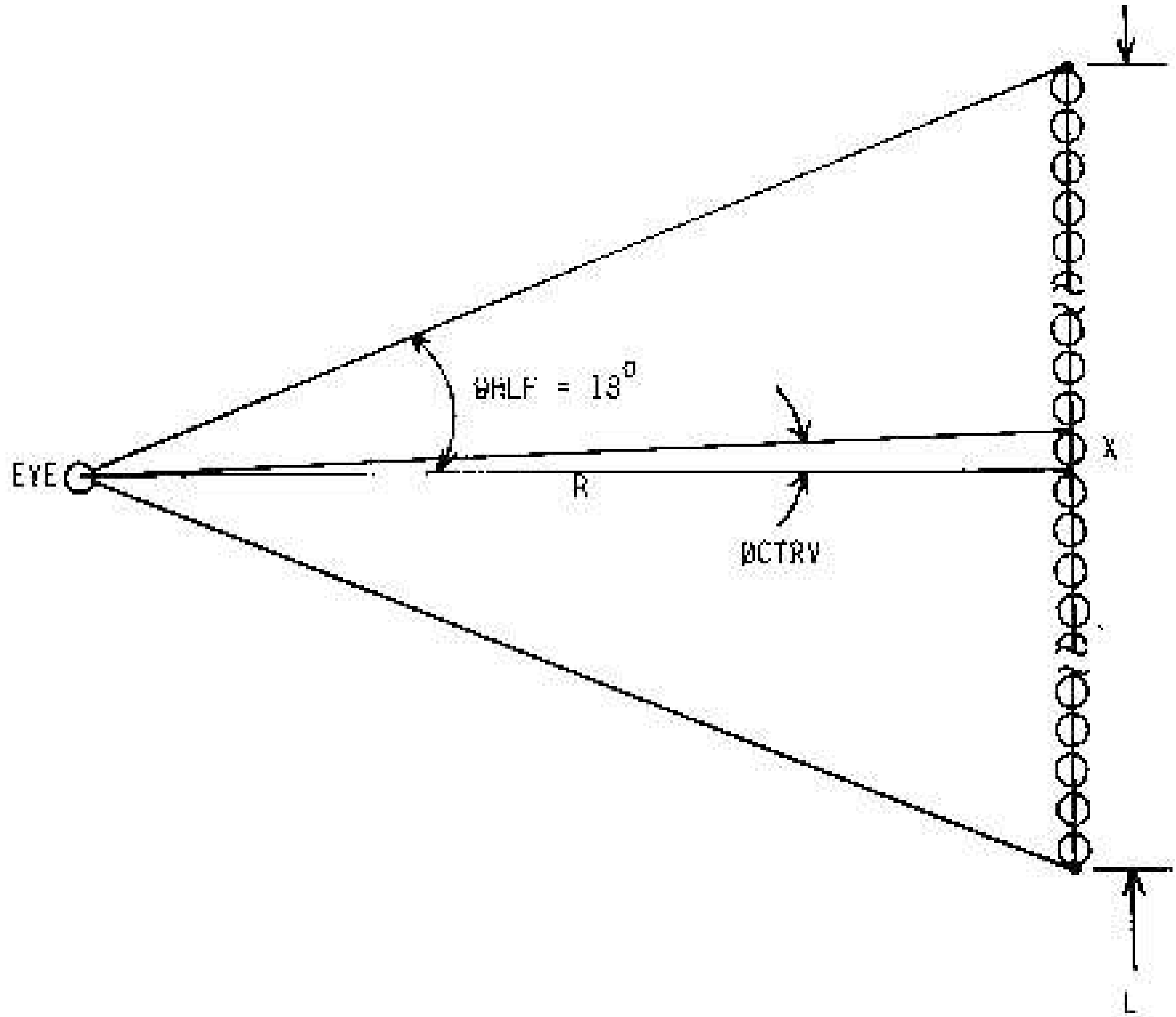


FIGURE 5.6 THREE-CHANNEL COLOR PROJECTION SYSTEM



TAN (ØCTRV) = X/R

X = L / #LINES

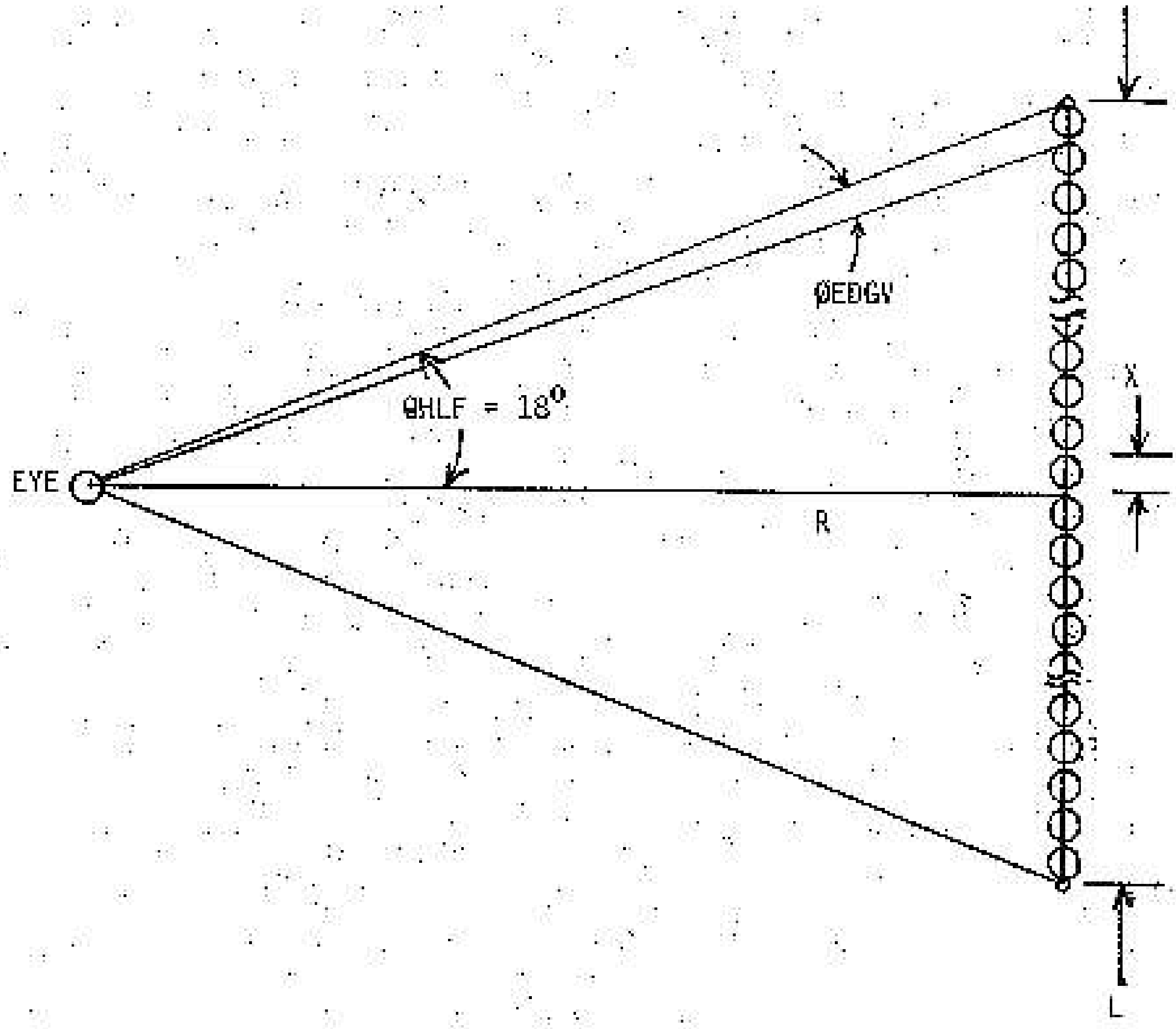
(L/2) / R = TAN (θHLF)

X/R = 2 * TAN (θHLF) / #LINES

TAN (ØCTRV) = 2 * TAN (θHLF) / #LINES

ØCTRV = ARCTAN ((2/#LINES) * TAN (θHLF))

FIGURE 5.7 VERTICAL RESOLUTION AT CENTER OF IMAGE



ØEDGV = ΘHLF - ARCTAN (((#LINES/2)-1) * X/R)

RECALL X/R = (2/#LINES) * TAN (ΘHLF)

ØEDGV = ΘHLF - ARCTAN (((#LINES/2) - 1) * (2/#LINES) * TAN (ΘHLF))

FIGURE 5.8 VERTICAL RESOLUTION AT EDGE OF IMAGE

Admittedly these more accurate resolution values do not reflect large errors accruing to the simpler calculations. The difference can be crucial, however, when a system must be judged compliant or noncompliant relative to a written specification.

Concerning brightness, assume that each screen is 6 feet by 8 feet and has a gain of 5. Given that the specified light output of the Aquastar is "500 lumens peak white", one is lead to conclude that the peak white brightness as seen by the pilot is:

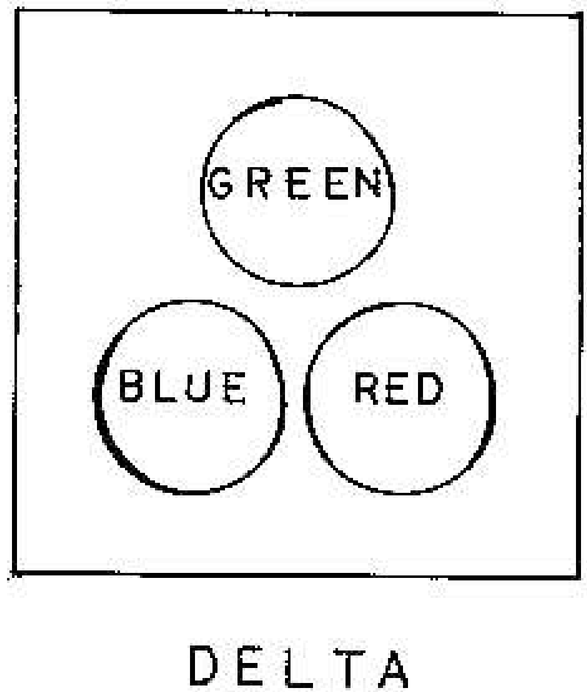
Brightness (Peak) = (500 lumens . 48 sq. ft.) * 5 = 52 ft. L.

This value is misleadingly large, however, since it is a common commercial practice to cite a peak brightness corresponding to only 20% of the screen being illuminated. And, unless explicitely called out in the specification, there is no guarantee that full resolution will be achievable concurrent with the peak brightness. When one insists on illuminating the entire screen concurrent with full resolution, the resulting peak brightness is usually several times less than that cited.

Another type of projector that has found its way into flight simulation is the full-color calligraphic projector. Unlike raster-scan devices, these projectors possess linear deflection capability demanding much more electrical power. Also, because drawing individual lights may involve phosphor dwell times that are more than 30x longer than those encountered with raster, protecting the phosphor from burns is much more critical but difficult to do. Two manufacturers of color calligraphic projectors are Rediffusion Simulation, Ltd. of Crawley, U.K. and Systems Research Laboratories of Dayton, Ohio. As shown in **Figure 5.9**, the three tubes are arranged in the projector either in a side-by-side linear manner or with a delta layout.

The projectors use one of two tube types: flat-face or Schmidt. The flat-face tube is as previously described in **Figure 5.1** and nominally has a 5-inch diagonal faceplate that allows a 3" by 4" image. The Schmidt tubes currently in use are configured as in **Figure 5.10** and are termed "Callibeam" by the manufacturer. The electron beam leaves the gun structure and passes through a central hole in a spherical projection mirror. It is incident on a convex aluminum target deposited with either red, green, or blue phosphor. The emitted light is collected by the mirror and reflects out of the tube after passing through an aspheric corrector lens to minimize aberration.

Each tube-type has its respective advantages and disadvantages. The flat-faced tube is more accommodating to different display geometries since off-the-shelf, individual lenses are available which handle different throw distances, image sizes, and screen curvatures. **Figure 5.11** shows the specification for a Delta II-D lens which is used in flight simulator applications. Given a 5" (127 mm) tube having a curvature greater than 5 meters, an image having a 3:4 aspect ratio can be projected by the lens onto any screen having a curvature greater than 138". An adjustment is provided for optimizing performance as a function of screen curvature. Similarly, an adjustment is provided for setting image size. The image diagonal is variable between 1270 mm (50") and 3000 mm (118"). Throw distance must correspond to 1–1/2 times the image width; i.e., it is variable between 75" and 177" in depending on the desired image size. The lens will provide a minimum resolution equivalent to 762 lines. This value will exist in the corner of the field; resolution of the center probably exceeds 1000 lines. The lenses are not achromatic (color-corrected) and function best at a single wavelength: 5461 Angstroms (green), 4800 Angstroms (blue), or 6438 Angstroms (red). This is not a problem when narrow-band phosphors are used; however, broad band phosphors such as P53 (green) having significant red and blue components will tend to have each color component focus in a different image plane and result in color fringing if care is not taken to filter the emitted light before projection. Some additional parameters worth noting are f/# = f/1.0 and lens transmission varies between $0.75 \le t \le 0.90$ depending on the degree of optical coating applied to the lens surfaces. These two parameters affect image brightness; their quantitative influence will be discussed shortly.



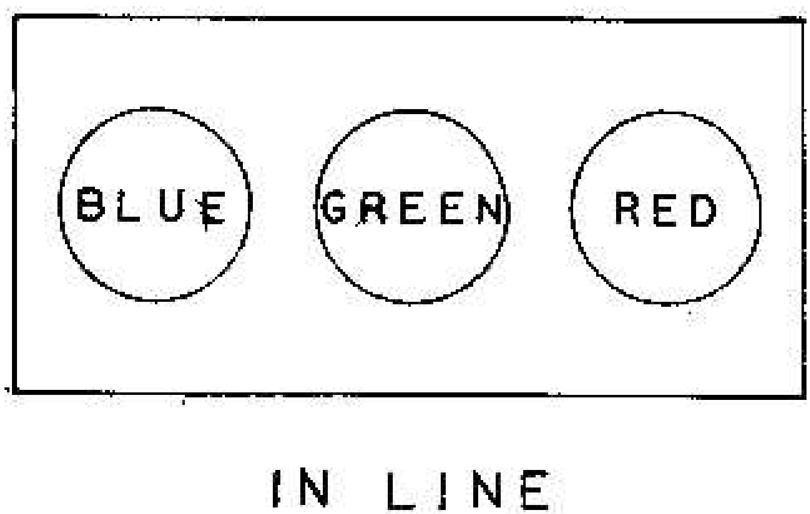


FIGURE 5.9 DELTA AND IN-LINE TUBE ARRANGEMENTS

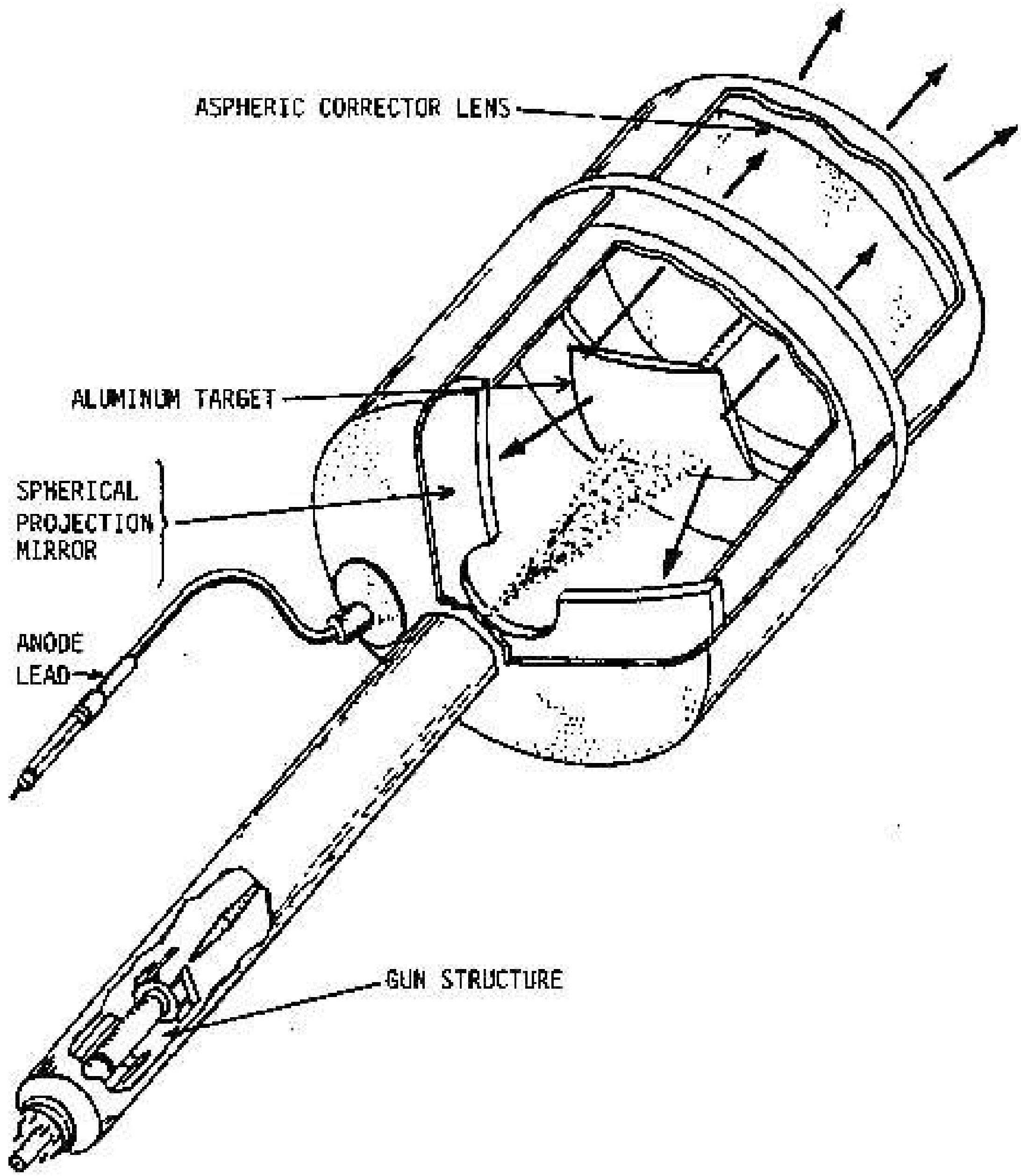


FIGURE 5.10 SCHEMATIC OF SCHMIDT PROJECTION TUBE

Focal Length .... 135.6mm @ 20X
f/# .... f/l.0, ±7%
CRT Diagonal 127mm
Phosphor Radius .... Flat, or curved (5m)
CRT Aspect Ratio .... 3 x 4
CRT Faceplate Thickness .... Variable, 5-16mm
Screen .... Front reflecting or rear transmitting
Screen Radius .... Nominal 5500mm radius, can be varied from 3500mm to infinity
Screen Diagonal .... Variable - 1270mm to 3000mm
Resolution .... Minimum of 5 line pairs per mm throughout field
Distortion .... Less than 1% nominal on flat screen
Transmission
  No Coating .... greater than 75%
  USPL #1 Coating .... greater than 85%
  USPL %2 Coating .... greater than 90%
Relative Illumination .... 30% at 95% of field
Color Correction .... Monochromatic
Design wavelengths (Angstroms) 5461, 4800, 6438
Element Material .... Acrylic (methyl methacrylate); U.L. Flamability Rating 94 HB

Mount Material(Black) .... Lexan 500
X-Ray Absorption in Lens .... Not significant

FIGURE 5.11: SPECIFICATION OF DELTA II-D LENS (U.S. PRECISION)

The Schmidt tube, as shown in **Figure 5.10** and again in **Figure 5.12**, is designed to produce an 84" diagonal image on a screen having a radius of curvature equal to 138", with a projector throw distance of 100". Once a tube is built these parameters are fixed unless additional optical elements are added to modify the projected light after it leaves the tube. The f/# = f/0.7, which is quite good for brightness. Brightness is also aided by the fact that light is emitted from the phosphor coating on the same side as the incident electrons. Hence, less attenuation occurs compared with a flat-faced tube since the latter requires the emitted light to penetrate the phosphor coating before being projected. **Figure 5.13** illustrates resolution as a function of image position. Minimum resolution occurs in the corners and equals 763 lines, which is comparable to that of the flat-faced tube. With regard to chromatic aberrations, any dispersion arising from broadband phosphors will be less with the Schmidt tube than with the flat-faced tube using a multi-element lens since the only optical components encountered by the projected light in the Schmidt are a mirror and thin corrector lens.

Brightness and brightness uniformity are important charac-teristics of any display system; however, they are especially critical in projection displays since the act of making an image on a large screen seems to be at odds with good brightness and uniformity. To understand the geometry and lens issues involved, an expression will be derived that relates screen brightness to tube brightness. Once obtained, its interplay with screen parameters (e.g., gain) will be discussed.

Consider the configuration shown in **Figure 5.14** in which a single CRT is projecting through a lens onto a perfectly diffusing reflective screen. This lens can be either a single element or the equivalent single lens representing a more complicated multi-element device. Regardless, it has a focal length F, effective aperture diameter D, and transmission T . The plane of the lens is a distance D1 from the CRT and a distance D2 from the screen. As stated previously, D1 and D2 are related via the expression:

$$(1/D1) + (1/D2) = (1/F)$$

Multiplying both sides by D2 and realizing that magnification M = D2/D1, one obtains:

$$(1 + M) = D2/F, \text{ or}$$
$$F2 * (1 + M)^2 = D2^2$$

Screen illuminance Es equals tube brightness Bt times lens transmission τ times the solid angle subtended by the imaging system at the screen. This solid angle is related to lens diameter and the separation D2 by:

$$\omega = PI * D^2/4/D2^2$$
$$Es = \tau * Bt * PI * D^2/4/D2^2$$

Substituting the previous expression for D2 into the last equation yields:

$$Es = \tau * Bt * PI * D^2/4/[F^2 * (1 + M)^2]$$

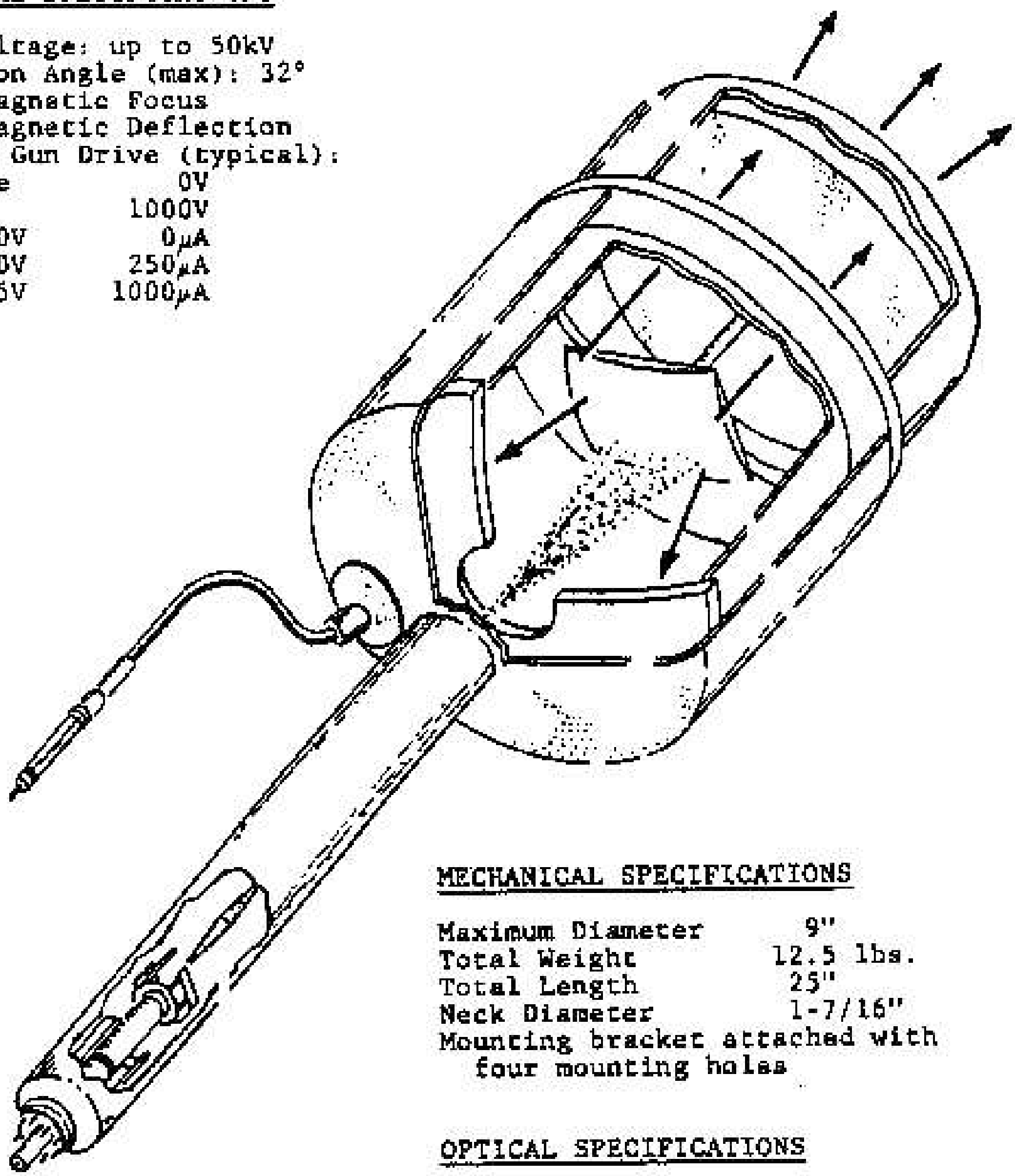
The f/# of this optical system is F/D, so

$$Es = \tau * Bt * PI/[4 * (f/\#)^2 * (1 + M)^2]$$

ELECTRICAL SPECIFICATIONS

Anode Voltage: up to 50kV
Deflection Angle (max): 32°
Electromagnetic Focus
Electromagnetic Deflection
Electron Gun Drive (typical):

Cathode	0V
G2	1000V
G1= -90V	0μA
= -50V	250μA
= -35V	1000μA



MECHANICAL SPECIFICATIONS

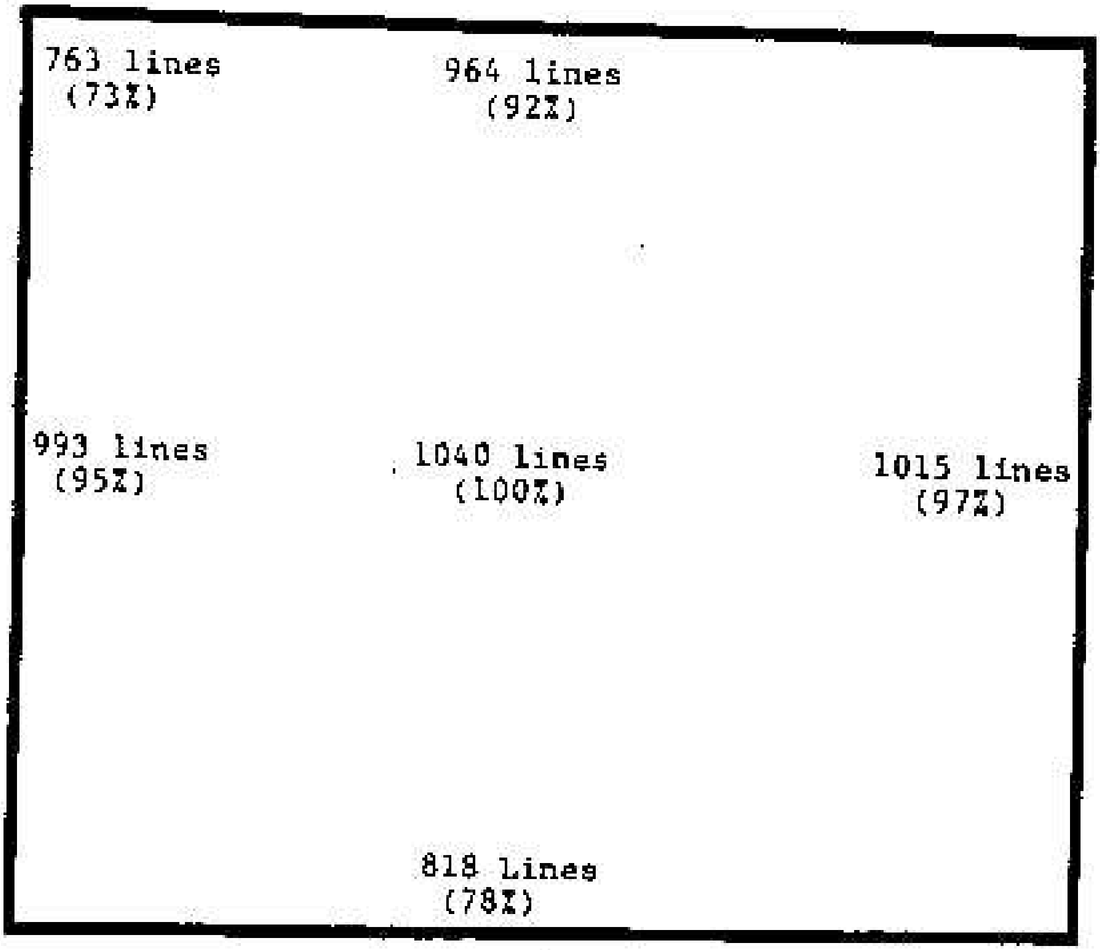
Maximum Diameter	9"
Total Weight	12.5 lbs.
Total Length	25"
Neck Diameter	1-7/16"

Mounting bracket attached with four mounting holes

OPTICAL SPECIFICATIONS

f/0.7 Schmidt Projection System
100" Throw Distance (nominal)
7' Diagonal Image (nominal)
11.5' Radius Image Curvature (nonimal)

FIGURE 5.12 CALLIBEAM DRAWING AND SPECIFICATION



RESOLUTION AS A FUNCTION OF IMAGE SCREEN POSITION
USING SHRINKING RASTER TECHNIQUE

FIGURE 5.13 RESOLUTION CHANGE OF SCHMIDT TUBE WITH SCREEN POSITION

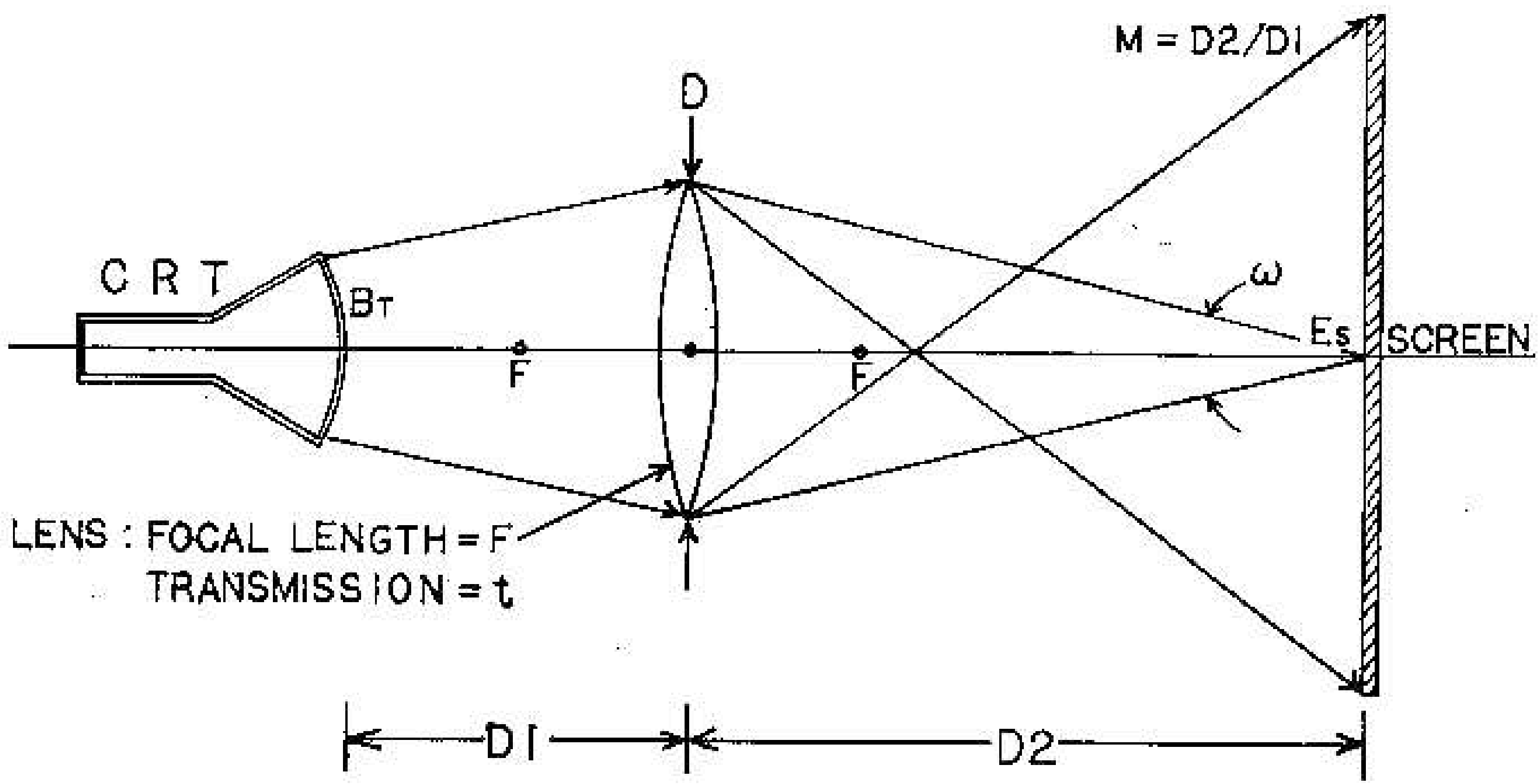


FIGURE 5.14 RELATING SCREEN ILLUMINANCE E_S TO TUBE BRIGHTNESS B_S

Completing this derivation requires that Es be related to screen brightness Bs. This relationship can be obtained somewhat circuitously by hypothesizing a half-sphere of radius R centered on an image element of area dS, as shown in **Figure 5.15**. The illuminance E' at the surface of the sphere is equal to:

$$E' = Bs * \cos\Theta * dW$$

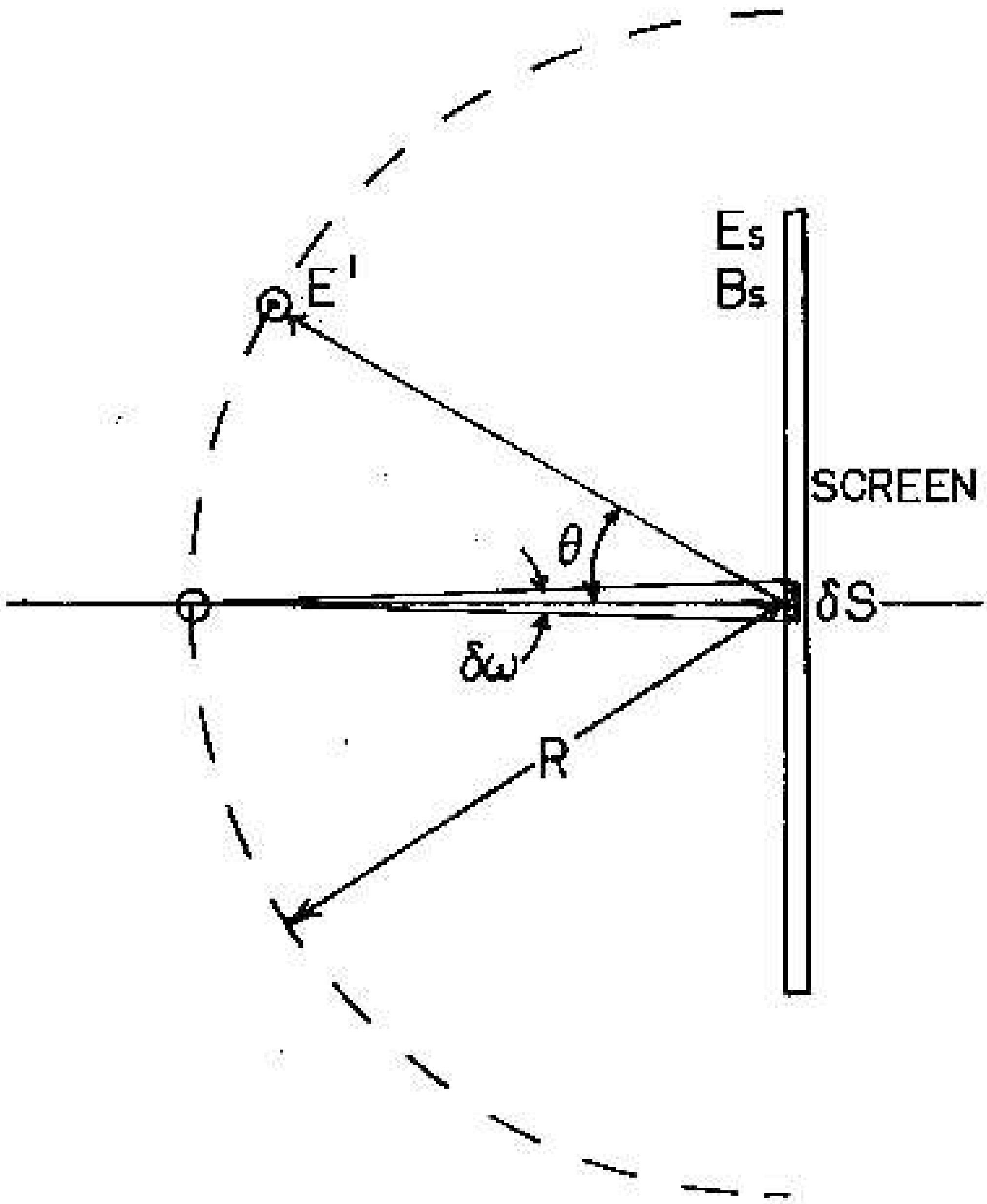
where Θ is the angle between the normal to dS and the point at which E' is measured, and dW is the solid angle subtended by dS from a distance R.; i.e.,$dW = dS/R^2$. If Es is integrated over the surface of the half-sphere, the above expression becomes one expressing total energy emitted by dS. Assuming a perfectly reflecting screen with no dissipation, conservation of energy demands that the total emitted energy equal the total incident energy, Es * dS. Performing the integration and setting energy equal to Es * dS yields:

$$Es * dS = Bs * dS * PI, \text{ or}$$
$$Bs = \tau * Bt /[4 * (f/\#)^2 * (1 + M)^2] \qquad (5.1)$$

The derived expression shows the roles played by lens transmission, lens f/#, and magnification. Brightness scales linearly with transmission, decreases quadratically with increasing f/#, and roughly decreases quadratically with magnification. By way of illustration, consider a display having a unity gain screen which is 50.4" vertically by 67.2" horizontally (i.e., 7 foot diagonal). Using a projector having "Callibeam" Schmidt tubes, what is the peak brightness (in ft.L.) produced by a uniform green raster? A reading of tube specifications indicates several needed facts: (i) target size is roughly 2.0" by 2.7", which implies m = 25, (ii) f/# = 0.7, (iii) τ is approximately 0.8 (or better), and Bt = 8100 ft.L. at a peak beam current of 500 microAmps (a reasonable level since resolution will still be adequate). Substituting these values into Equation 5.1 yields a screen brightness Bs = 4.9 ft.L., or 0.06% of the luminance as measured at the phosphor!

Alternatively, consider the same example but instead use flat-faced tubes and Delta IID lenses. Generously assuming the same tube brightness Bt = 8100 ft.L., lens data implies that the other parameters must take on values of (i) M = 16.8, (ii) f/# = 1.0, and (iii) τ = 0.75 (uncoated). Substituting these values into Equation 5.1 yields a screen brightness Bs = 4.8 ft.L., which is nearly identical to that of the Callibeam. It would appear that the lower f/# of the Schmidt tube was offset by the reduced magnification needed for the flat-faced tube!

The value for peak brightness is generally attained only at the center of the image. Because the electron beam is incident on the phosphor at an increasingly large angle as the edge of the tube face or target is approached, the amount of emitted light tends to roll off. In a direct-view CRT such as the 25" displays discussed previously, the large deflection angles (about 45°) result in a peak corner brightness of approximately 40% of that at the center. The deflection angles in projection CRT's are much less, thus resulting in less roll off at the edges. However, the tendency of the projection optics, whether Schmidt or lens, is to present a smaller effective pupil to the phosphor as the edge of the phosphor is approached. As a result, the peak brightness at the edge of a projected image will diminish accordingly. **Figure 5.16** shows brightness as a function of screen position for a Schmidt tube. Worse case edge brightness is 33% of that at the center. Put another way, brightness uniformity is ±67% relative to center brightness.



$$Bs = t \times Bt / (4 \times (F\#)^2 \times (1 + M)^2)$$

FIGURE 5.15 RELATING SCREEN BRIGHTNESS Bs TO SCREEN ILLUMINANCE Es

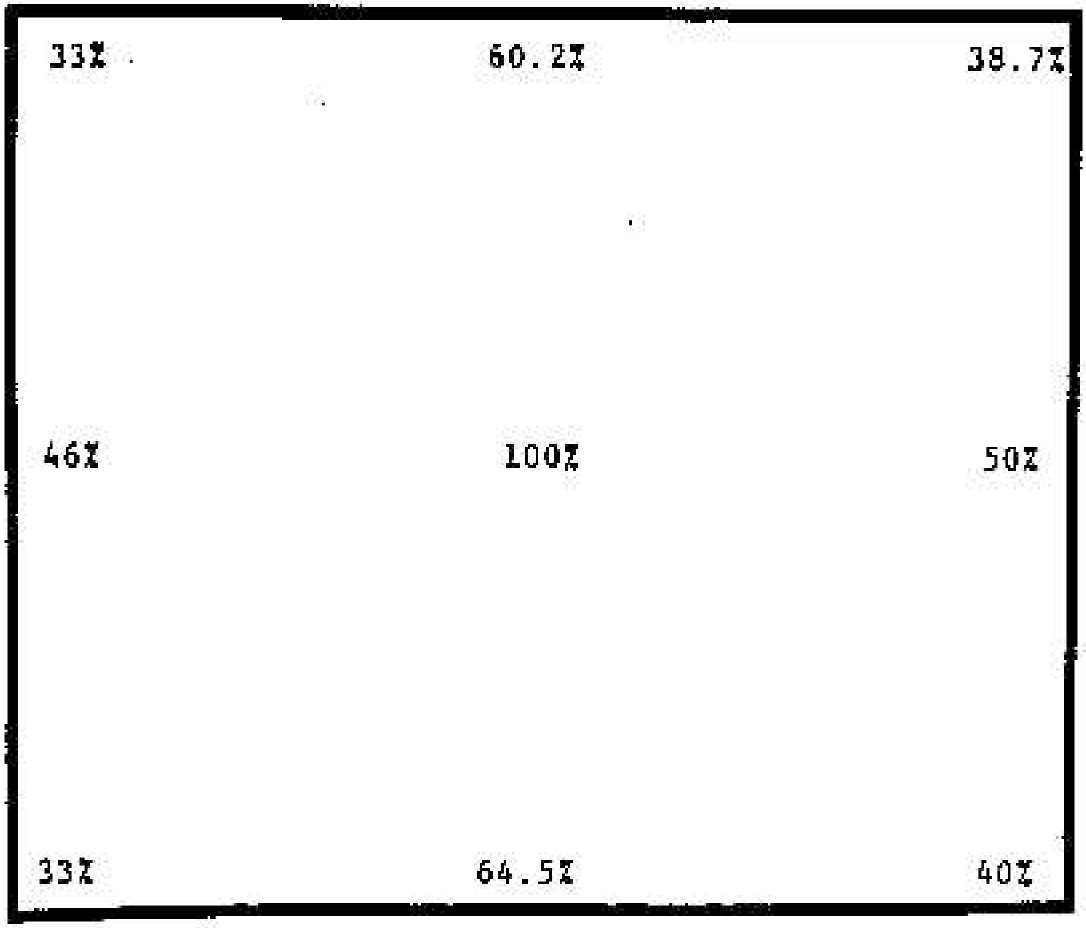


FIGURE 5.16 BRIGHTNESS CHANGE OF SCHMIDT TUBE WITH SCREEN POSITION

Regrettably, diminishing of brightness uniformity does not necessarily stop after the light leaves the projector. Consider a display geometry discussed previously and illustrated in **Figure 4.3**. Assume rear projection onto a perfectly diffusing 6 foot by 8 foot screen that is 50% transmissive by using a calligraphic projector having flat-faced tubes. Furthermore, white raster with peak brightness of 6.0 ft.L. is considered necessary for effective daylight simulation. Though the P53 green tube is capable of 8100 ft.L., the P56 red and P55 blue can only provide 4000 ft.L. and 1000 ft.L., respectively. Since white is composed of 60% green, 30% red, and 10% blue, green must be attenuated to 6000 ft.L. and red to 3000 ft.L. so as not to overdrive blue. Thus, a white brightness of 10,000 ft.L. is produced by the tubes. Using M = 24, f/# = 1.0, lens $\tau = 0.8$ (coated), and screen $\tau = 0.5$, the peak screen brightness is 1.6 ft.L.; i.e., 1/4 of that required. Brightness uniformity will be ±67% due to roll-off in the projected image as discussed previously.

The most straightforward method for obtaining needed additional brightness is to use a screen having a higher value of gain. A perfectly diffusing screen that is 100% reflective and viewed in reflection is said to have unity gain. Such a screen is often simulated for measurement purposes using a magnesium carbonate material (cf. white chalk) that is about 90% reflective and nearly a perfect diffuser. A perfectly diffusing screen that is 50% transmissive and viewed either in transmission or reflection will have a gain of 0.5. For this example, a screen having gain equal to 6/(2 * 1.6) = 1.88 is required to achieve a peak brightness of 6.0 ft.L.

Increased peak brightness is not obtained without a price. Conservation of energy mandates that directing more light energy in one direction necessitates that it be diminished in others. Put in terms of antenna theory, going from unity to higher screen gain results in the screen changing from a uniform radiator to one having a narrower radiation lobe. **Figure 5.17** shows relative brightness vs. bend angle (relative to the axis of the principal incident ray) for a representative screen material having a gain of 1.9 (LS50 from 3M). Note that brightness in a direction 30° from the principal axis is already reduced to 26% of that along the principal axis (100%). The top of **Figure 5.18** shows an actual implementaton of the projection display of **Figure 4.3**. The bottom picture examines the bend angle required to get light passing through the corners to the pilot; this is the "worse case" bend angle encountered. The eyepoint is on-axis and 9 feet from the screen to ensure a 36° by 48° FOV. The drawing indicates that the angle involved is 52°. Using **Figure 5.17**, the corners will have 10% of the peak brightness (on center). As a result, going from a perfectly diffusing screen having gain = 0.5 to a screen having gain = 1.9 increases peak brightness from 1.6 to 6.0 ft.L., but decreases brightness uniformity from a relative corner brightness of 33% to one of 3.3%. Such a large brightness roll-off is unacceptable in flight simulation since it serves to effectively truncate the FOV below the specified value of 36° by 48°.

5.4 Full-Color, Shadow Mask CRT Monitors

Another way to generate a full-color image, and the most common way, is to use a shadow mask CRT, so-called because a thin sheet of finely perforated metal—a shadow mask—sits next to the phosphor between it and the electron guns. Unlike the single electron gun used in a monochrome tube, a shadow mask tube has three such guns (one each for red, green, and blue) oriented either in-line and parallel, or in a delta arrangement and tilted slightly in towards the axis of symmetry. The phosphor coating, rather than being uniformly of one color, is composed of three intermeshed arrays of dots or stripes, each array containing either dots of stripes of RGB. The shadow mask is carefully fabricated and positioned in the tube to ensure that each electron gun can address only that array of dots or stripes corresponding to the color information being supplied to the gun.

LS50

This product is similar in light distribution to LS80 except that it is slightly darker in color. This darker color makes it an ideal screen to reduce washout of an image because of reflected light from a mirror which is close to the screen.

Nominal Gain:	LS50 NY	1.90 ± 0.38
	LS50 BL	1.90 ± 0.38
	LS50 GR	1.90 ± 0.38
Reflectance:	0.10 (10%) at 30°, or less	
Resolution:	50 Line pairs/mm, or better	
Half Brightness Angle:	19° (avg.)	
Transmittance:	LS50 NY	42 ± 5%
	LS50 BL	42 ± 5%
	LS50 GR	42 ± 5%
Viewing Angle:	70° (35° from either side of a perpendicular to the screen surface, at center)	

Available in all standard substrates and thicknesses.

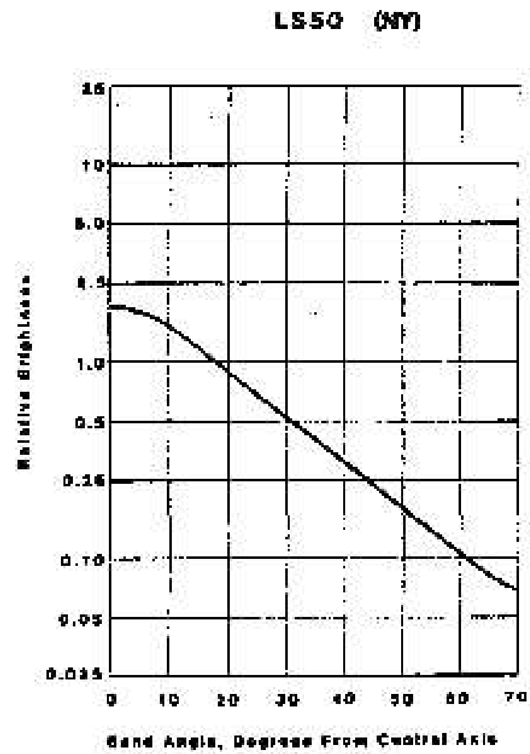


FIGURE 5.17 BRIGHTNESS VARIATION WITH BEND ANGLE FOR LS50 (3M)

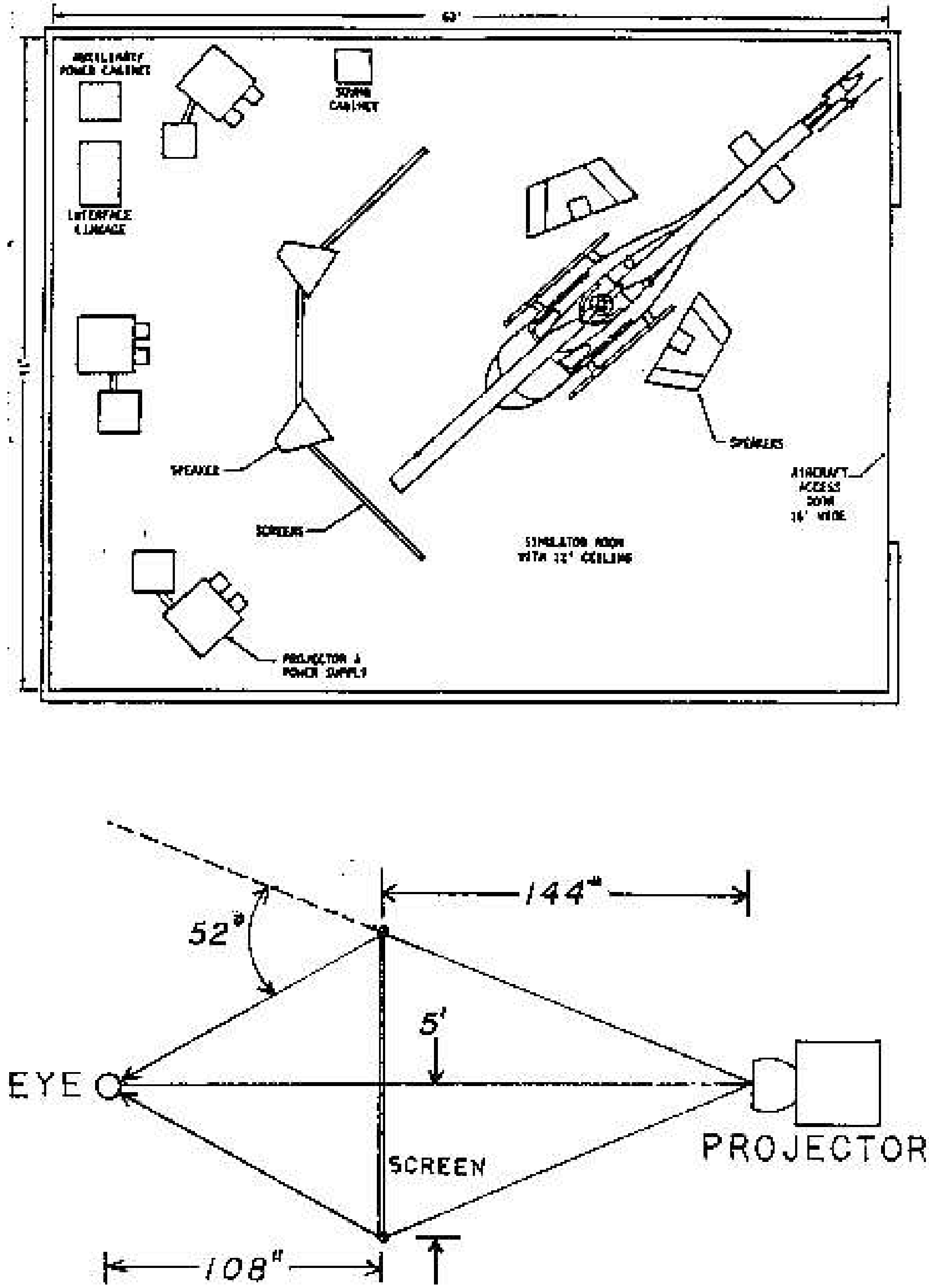


FIGURE 5.18 REAR PROJECTION DISPLAY AND BEND ANGLE CALCULATION

Figure 5.19 illustrates the three possible gun/shadow mask/phoshor structures. The first configuration uses the delta-gun in conjunction with the round aperture shadow mask. The second and third ones use the in-line gun arrangement, but with a round aperture shadow mask and slotted aperture shadow mask, respectively. The favored configuration for high-resolution, 25-inch diagonal displays is the delta gun with round aperture shadow mask. Apparently the self-converging deflection yoke used for the in-line gun systems produces excessive astigmatism when the beam is deflected through the large angles characteristic of 19-inch or larger tubes; this is not the case for the delta gun with its less efficient deflection yoke.

When compared with the simpler monochrome tube, the shadow mask tube has reduced performance with the exception of color rendition, which is comparable to that of the color CRT projector. Brightness suffers since areas of the shadow mask not containing apertures keep electron energy from reaching the phosphor. Some compensation is possible by increasing beam current. However, care must be exercised so as not to saturate the phosphor or excessively heat the shadow mask; the latter will result in thermal distortions which destroy color purity. Brightness in excess of 50 ft.L. is achievable using these tubes. Resolution suffers owing to the discontinuous nature of the shadow mask and phosphor layer. The smallest displayable object must be at least as large as several RGB phosphor triads to ensure accurate color rendition, especially if the object must move across the face of the CRT. A commonly used 25-inch Panasonic shadow mask tube having a triad pitch (spacing) of 0.37 mm is capable of displaying roughly 1100 TV lines.

5.5 Light Valve Projectors

In applications where high image brightness is of paramount importance, the Light Valve (LV) Projector has much to contribute. Unlike a CRT in which brightness has a direct relationship to the cathodoluminescene of the phosphor, a LV Projector uses an electro-optic material to spatially modulate the brightness of a (potentially) very bright light source. **Figure 5.20** illustrates the LV concept. A LV material having spatially-varying transmission is used to modulate a bright source of light. In this way the LV is the optical 2-D analog of a transistor. Whereas a transistor controls a large collector current via a smaller base current, the LV controls the high brightness of a 2-D image via low-energy modifications to the physical or electro-optic properties of the LV material.

The LV concept is not a particularly new one; a common example is a household slide projector. What is new, however, are materials and techniques that permit the LV to be updated at real-time rates, thus enabling them to display computer-generated imagery. Some of the LV Projectors currently in use are the EIDOPHOR Large Screen Television Projection System, the GE Talaria Projection System, the Hughes Liquid Crystal Light Valve Projector, and the Sodern Visualization System. Each will be briefly described and its attributes discussed.

Figure 5.21 illustrates the modulation mechanism used in the EIDOPHOR Projector. It is comprised of six main elements:

1. A 2.5 kW Xenon arc lamp acting as a high intensity light source,
2. A condenser lens system for collecting the luminous flux of the arc lamp,
3. A spherical mirror carrying a thin film of viscous liquid, termed the "EIDOPHOR Control Layer",
4. An optical system featuring a set of 45∞ tilted mirror bars which are located at an axial distance from the mirror of twice the mirror's focal length,
5. Projection optics for imaging the surface of a spherical mirror onto a projection screen, and
6. An electron gun structure accompanied by deflection yokes and focus coil.

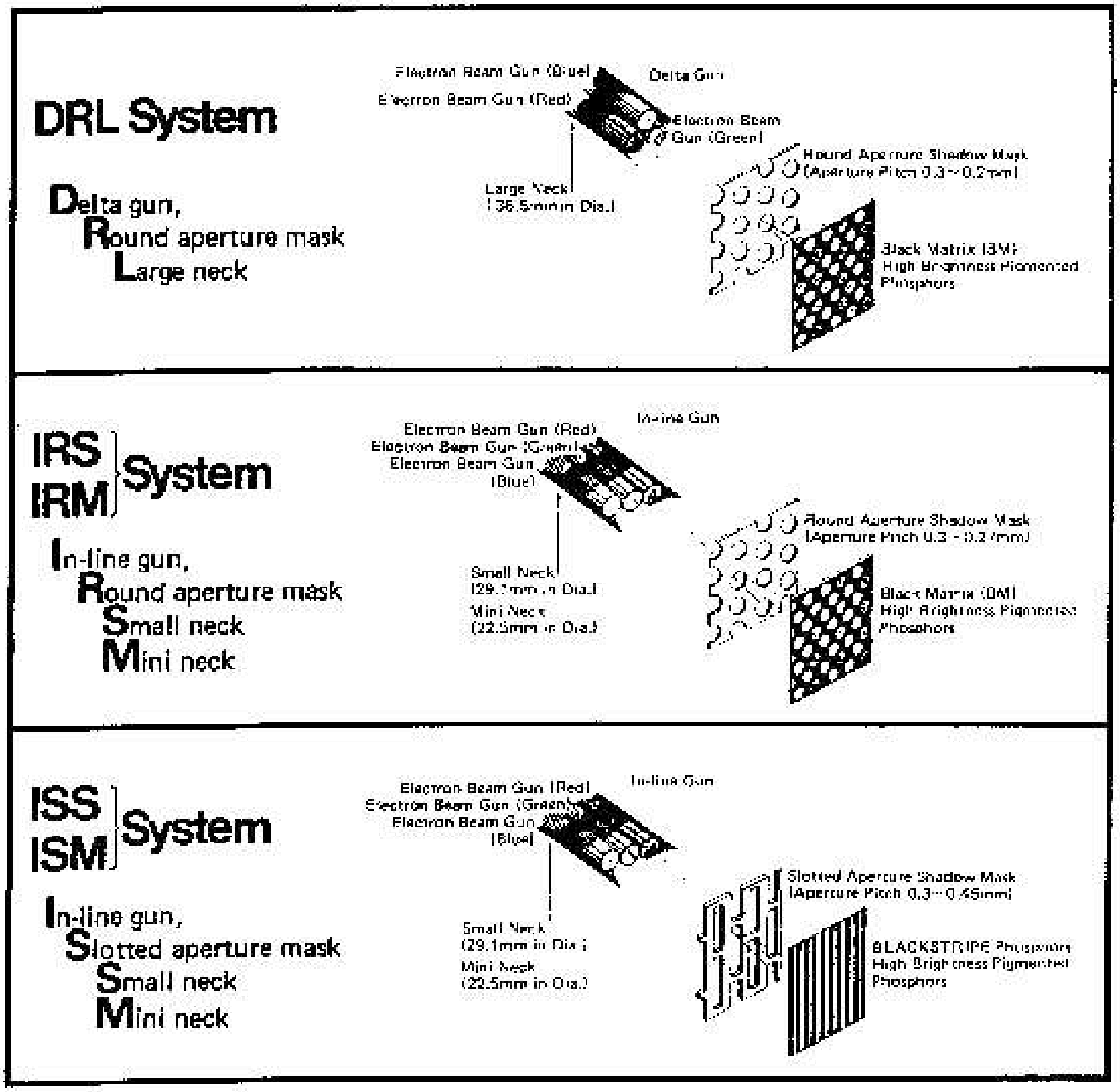


FIGURE 5.19 THREE GUN/SHADOW MASK/PHOSPHOR CONFIGURATIONS

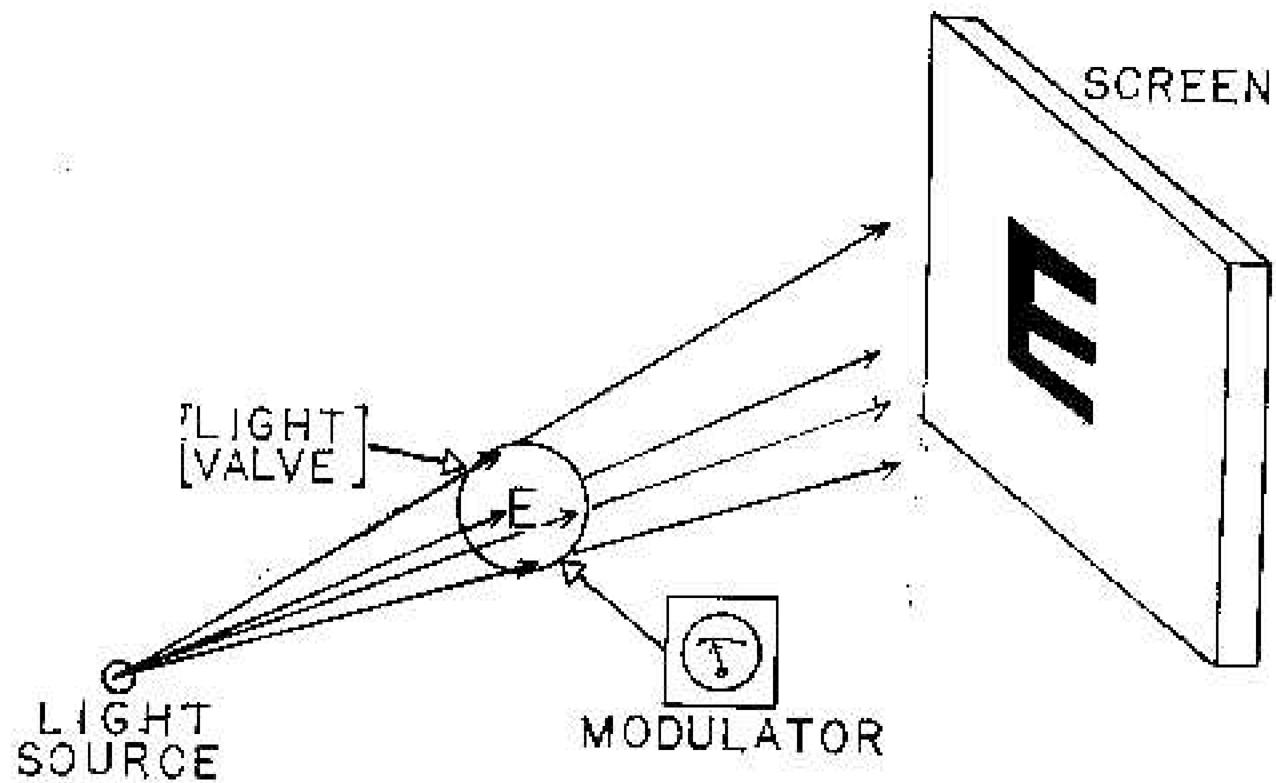


FIGURE 5.20 SCHEMATIC OF LIGHT VALVE CONCEPT

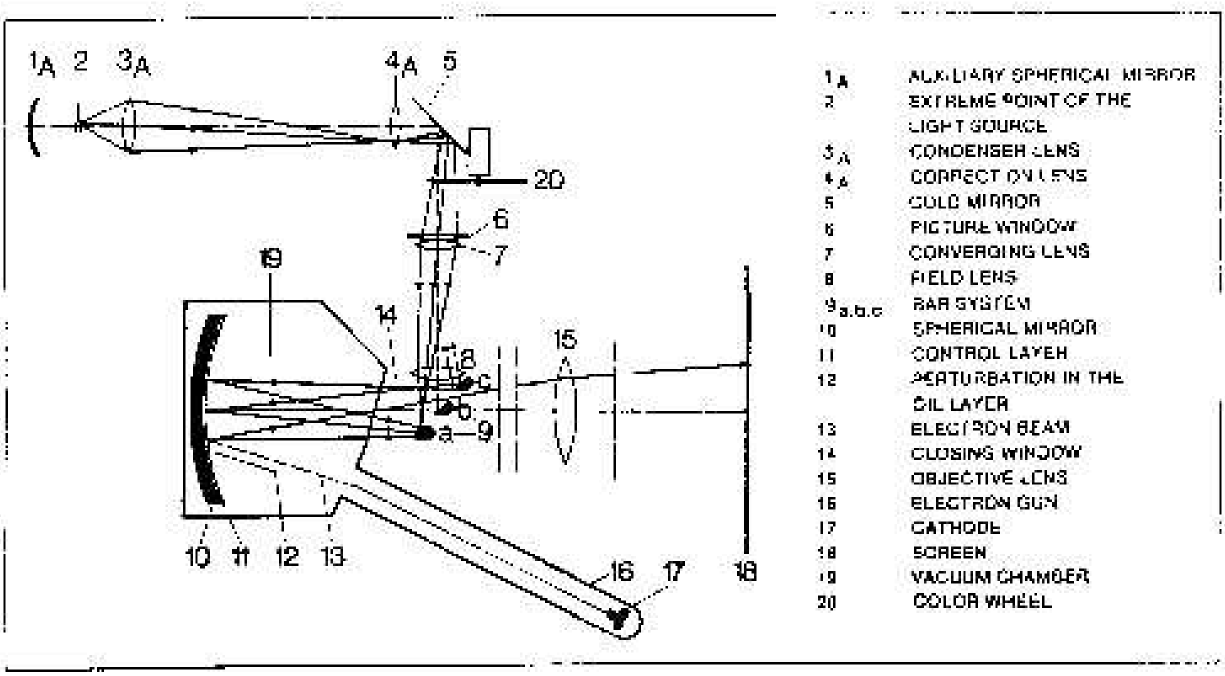


FIGURE 5.21 MODULATION MECHANISM OF EIDOPHOR PROJECTOR

The interaction among these elements for producing a large screen image begins with the light flux from the Xenon lamp being directed onto the spherical mirror via the condenser lens assembly and the 45° tilted mirror bars. Normally the film of viscous liquid on the spherical mirror reflects incident light back onto the tilted mirror bars, and from there back to the Xenon lamp. However, if the transparent EIDOPHOR Control Layer is deliberately distorted by electrical charges, reflected light can be deflected so that, instead of following the original path and returning to the arc lamp, it bypasses the tilted mirror bars by an amount proportional to the depth of the control layer deformation and appears on the projection screen. The electrical charges leading to control layer distortion are the result of video modulating the electron beam being scanned across the control layer. This raster scan leads to a complete 2-D black-and-white image in which overall brightness is proportional to the power applied to the Xenon arc lamp, but spatially-varying local intensity is proportional to video modulation. Such a system in which the image is normally dark except where diffraction occurs is termed a "schlieren" optical system.

Full-color is obtained by either field sequential operation or simultaneous operation of three light valves. The former utilizes a color wheel between the Xenon lamp and tilted mirror bars to temporally separate red, green, and blue light. Tripling the field rate and modulating each color appropriately yields a sequential tri-color set of monochrome images which the eye integrates into a full-color image. Alternatively, the latter scheme uses three separate light valves to simultaneously generate red, green, and blue components of imagery, producing a full-color image in a manner similar to the three-tube CRT projector.

Brightness of a full-color EIDOPHOR Projector such as the Gretag 5170 shown in **Figure 5.22** is as high as 3600 lumens at image center with full white modulation. On a 1200 square foot screen (i.e., 30 feet by 40 feet) of gain = 1.6, this implies a brightness of 4.8 ft.L. Contrast exceeds 100:1. Resolution of each color channel is at least 800 TV-lines at the center of each picture, decreasing to no less than 550 TV-lines within a circle of diameter equal to picture width. Color convergence is better than 0.1% of picture height within a circle of diameter equal to 0.8x of picture height, and better than 0.25% in the rest of the picture. Put another way, in an image subtending 36°by 48°, worst-case color misregistration is ±6 arc-minutes.

The EIDOPHOR Projector produces excellent imagery but is big and bulky, expensive to buy and maintain, and does not appreciate excessive motion or vibration. Strictly speaking, it should not be discussed in the present context since it has not been employed in a flight simulator using CGI. For example, five projectors are driven by CGI in the Computer Aided Operations Research Facility (CAORF) at the National Maritime Research Center; however,the training environment is the wheelhouse of a ship rather than the cockpit of an aircraft. Similarly, EIDOPHOR Projectors have been used for the Space Shuttle training program and a helicopter simulator of the Iranian Air Force, but these use model board/TV camera input rather than CGI. Regardless, discussing the EIDOPHOR is justified here for two reasons. First, it could be used for CGI-driven flight simulators in situations where its size, weight, and motion sensitivity are not a detriment. Second, the modulation principal is similar to that of the GE Light Valve Projector. Thus, discussing the EIDOPHOR serves as an introduction to a device that has historically played an important role in CGI-related flight simulation.

The GE Talaria Light Valve Projector, like the EIDOPHOR projector just described, utilizes a Xenon arc lamp, deformable fluid layer, and schlieren optical system to generate a projected image having high brightness. The GE system, however, differs in that the deformable fluid is constantly refreshed from an oil reservoir to achieve long life for the light valve assembly, generally the most costly expendable part of the projector.

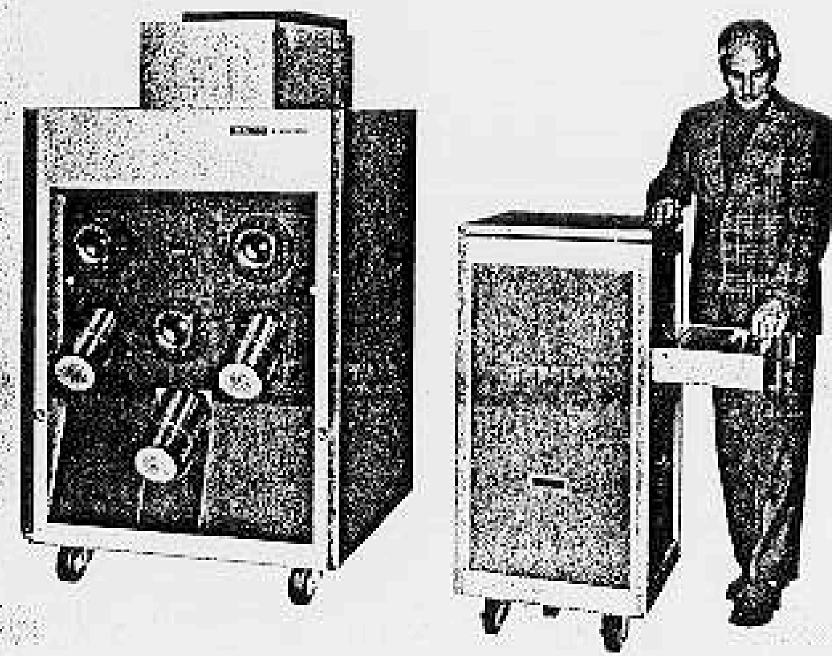


FIGURE 5.22 PICTURE OF GRETAG 5170 PROJECTOR

Another important difference is that GE achieves "simultaneous" full-color while utilizing only a single light valve assembly. **Figure 5.23** illustrates how this is accomplished. Emitted white light from the Xenon lamp is filtered so the green and magenta (red + blue) components pass through an input mask having horizontal and vertical slots, respectively. When no modulation is present, the intensity pattern created by the input slots is exactly imaged onto an output mask containing bars that block the passage of light to the screen; i.e., the schlieren optics produce a dark image field. To form a green image, the spacing between horizontal raster lines is modulated by wobbling the electron beam at a fast rate using vertical deflection, thereby creating a horizontal phase grating in the oil film. The amount of modulation controls the amount of vertical diffraction and subsequently the amount of green light that can pass the horizontal output bars and reach the projection screen. Red and blue are modulated by diffraction gratings generated at right angles to that for green by velocity modulating the electron beam. A 16 MHz signal added to the horizontal deflection produces a vertical grating that can horizontally diffract red light past the vertical output bars while blocking blue. Similarly a 12 MHz signal will produce a grating that can diffract blue light past the bars while blocking red. Thus, three primary color pictures are simultaneously written with the same electron beam and projected to the screen as a completely registered full color picture.

A typical Talaria projector is shown in **Figure 5.24**. A top-of-the-line projector such as the PJ5155 will raster scan an image having 1023 lines at 60 Hz field rates and produce a minimum resolution for a white picture of 750 TV-lines horizontally by 650 TV-lines vertically; i.e., 1000 pixels horizontally by 650 pixels vertically. Maximum brightness is 2000 lumens. As stated previously, exact color registration is inherent to the device.

Compared to other light valve projectors, the GE device is relatively affordable in terms of cost and maintenance. However, its maintenance costs still run higher than most CRT projectors. Another drawback is that its raster structure must remain unperturbed so as not to disturb the generation of the three phase gratings. This restriction precludes electronic image compensation of picture distortion arising from off-axis projection or projection onto spherical surfaces—both common occurences in flight simulation. Resolution of white imagery is also lower than that achievable by comparably-sized CRT projectors. In fact, maximum resolution is only achievable for the color green (the main spectral component for white). Resolution for red and blue is less than half that of green. Color purity suffers in small objects owing to the finite extent of the diffraction gratings generating the color components. Despite these limitations, the Talaria Projector plays an important role in display systems requiring B/W or full-color raster imagery having high brightness, above average resolution, and no need for correcting geometric distortion electronically.

The Hughes and Sodern Light Valve Projectors differ from the EIDOPHOR and GE devices principally in the type of light valve material. Whereas the latter two use deformable viscous fluids, Hughes and Sodern use electro-optic materials. Without going into detail concerning the theory of operation, suffice it to say that Hughes uses a nematic liquid crystal to modulate the projection light whereas Sodern uses a Pockels crystal. Each spatially alters the polarization characteristics of the projected light and, when used with a polarization-sensitive optical system, yields a modulated 2-D image. Full color is achieved for both by using three separate light valves simultaneously.

A simplified illustration of the Hughes HDP-2000 monochrome projector is shown in **Figure 5.25**. The upper section illustrates the sandwich structure of the light valve, whereas the lower section shows how it interacts with a Xenon arc lamp and projection lens. This particular projector is based on a cadmium sulphide photoconductor and has been used, for example, by NASA in their Shuttle Mission Simulator. Brightness exceeds 500 lumens, and resolution exceeds 1000 TV-lines. Both raster and calligraphic input are permissible. The major drawback to the Hughes CdS-based light valve is persistence; noticeable tailing is observed in dynamic imagery. Hughes is currently developing a silicon-based light valve that will possess improved persistence characteristics. Though full-color is possible, it is not yet a commercially-proven entity.

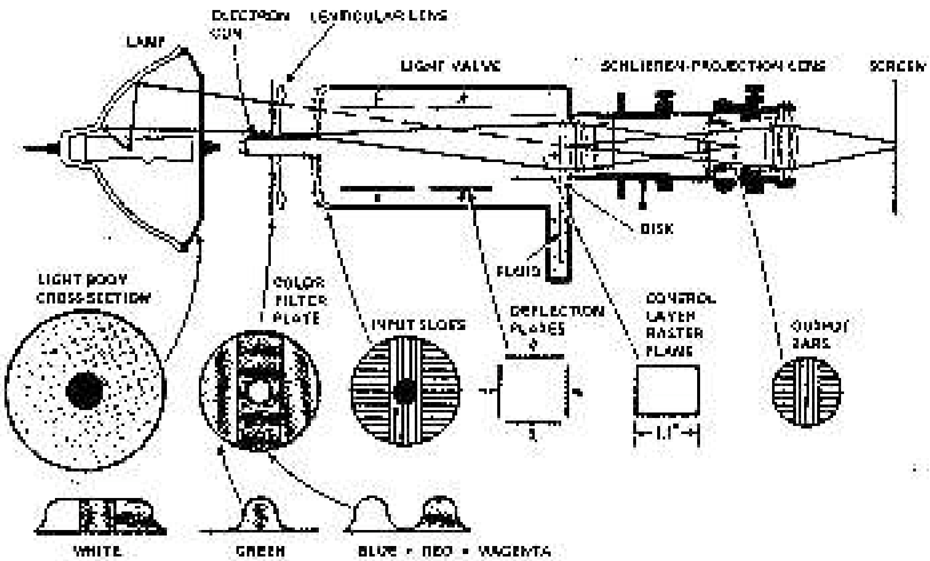
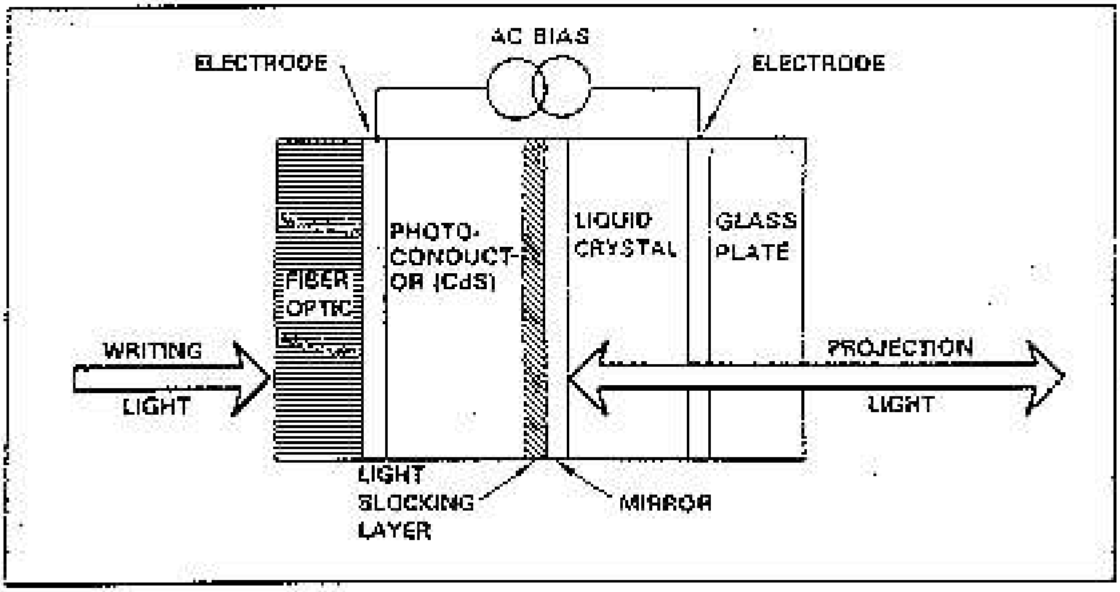
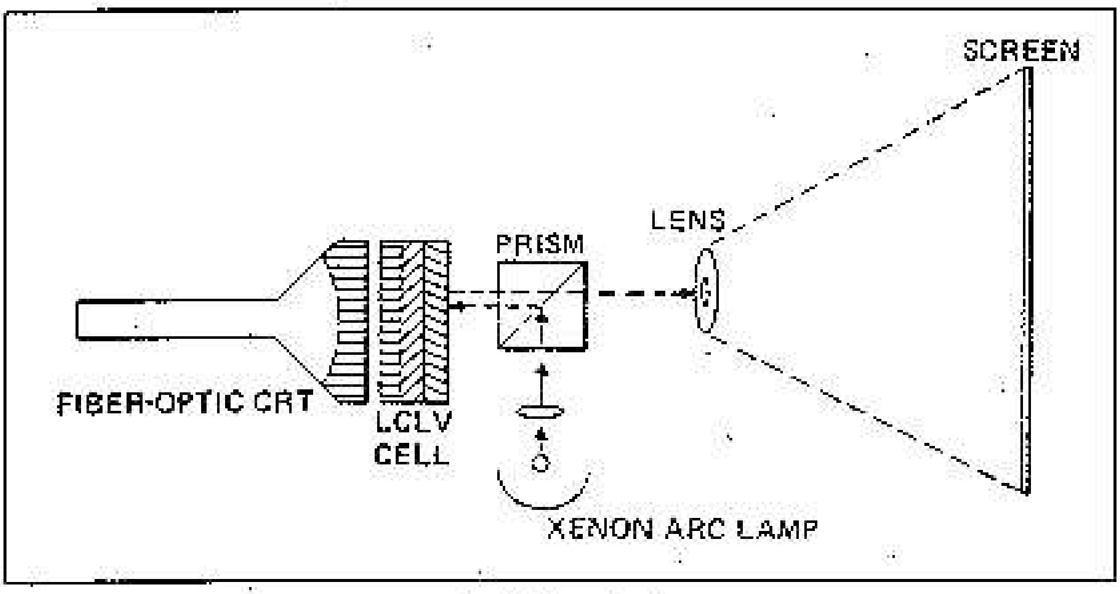


FIGURE 5.23 SCHEMATIC OF GE LIGHT VALVE

FIGURE 5.24 TALARIA PROJECTOR



Construction of Liquid Crystal Light Valve



Single-Channel LCLV Projector

FIGURE 5.25 HUGHES LC LIGHT VALVE AND PROJECTION MECHANISM

A schematic of a Titus Light Valve used by Sodern is shown in **Figure 5.26**. Electric charges deposited on the DKDP crystal locally alter the birefringence, thus enabling linearly polarized light from the Xenon lamp to be modulated. Implementation of a color system employing three light valves is shown in **Figure 5.27**. Brightness of the full-color SVS 14 projector can be as high as 2500 lumens when used with a 4kW Xenon arc lamp. Resolution is roughly 800 TV-lines vertically by 800 pixels per line horizontally; an aspect ratio of 1:1 takes best advantage of available brightness and resolution. Color convergence is better than 0.05% of picture height in a circle of diameter equal to 80% of picture height and centered within the picture. Worse-case misconvergence is 0.15% of picture height as measured in the corners of the picture. Geometric distortion inside the 80% circle is less than 0.3% of picture height. All projectors built thus far have been raster scan devices with up to 1024 lines at 60 Hz field rates and 2:1 interlace. In principle, calligraphic operation is supportable as well.

One especially interesting characteristic of the Titus Light Valve is its inherent memory; i.e., a pixel stays turned on or off until it is readdressed by the electron beam. The effect on the observer is that no image flicker is apparent, even at high levels of brightness. Care must be taken, however, to ensure that the light valve is driven with a suitably high beam current. Otherwise, not enough electrical charge can be removed from the Pockels crystal in a frame time and tailing of dynamic objects appears in the imagery.

The Air Force Human Resources Laboratory (AFHRL) at Williams AFB recently took delivery of an SVS 14 projector under the auspices of Project 2363. Test results are encouraging; however, parameters such as resolution, contrast, and image persistence still leave something to be desired. And, as shown in **Figure 5.28**, it is a rather large and heavy unit to work with, especially if more than one is required on a motion platform. Initial and recurring maintenance costs are high as well. For some applications, however, it continues to show great promise owing to its high brightness and capability to electronically correct geometric distortion.

6.0 Existing Display Systems

Since the early 1970's when CGI was first employed for flight simulation, a wide range of display systems have been applied to various training tasks. Initially these displays were based on calligraphic input devices because vectors and individual lights were less expensive to generate from the IG standpoint. The results were systems containing very simple imagery such as a runway in which take-offs and landings could be practiced at dusk or night. Raster capability was added soon thereafter to provide surface detail such as runway stripes. As computer memory prices dropped, however, large video buffers supporting bit-mapped graphics became affordable. This led to raster-scan and improved raster/calligraphic systems with richer scene content and a capability permitting full-daylight training.

The following section describes and compares virtual and real image systems. The next five sections then describe some specific display systems used in flight simulation; they are not intended to be all-inclusive. The goal is to represent the range of display configurations possible, and to discuss why one system is chosen over another for a particular training application.

6.1 Virtual Vs. Real Image Systems

A virtual image system, as previously discussed in Section 4.0, is one that collimates the imagery viewed by a trainee. Recall that an advantage of such a system over a real image system is that angular positions of objects in the image do not change with lateral head motion. For example, consider the landing task and assume the pilot has just lined himself up with the runway centerline. If the pilot moves his head right or left, a virtual image system will guarantee that a false cue is not generated telling the pilot that he is no longer properly aligned with the runway.

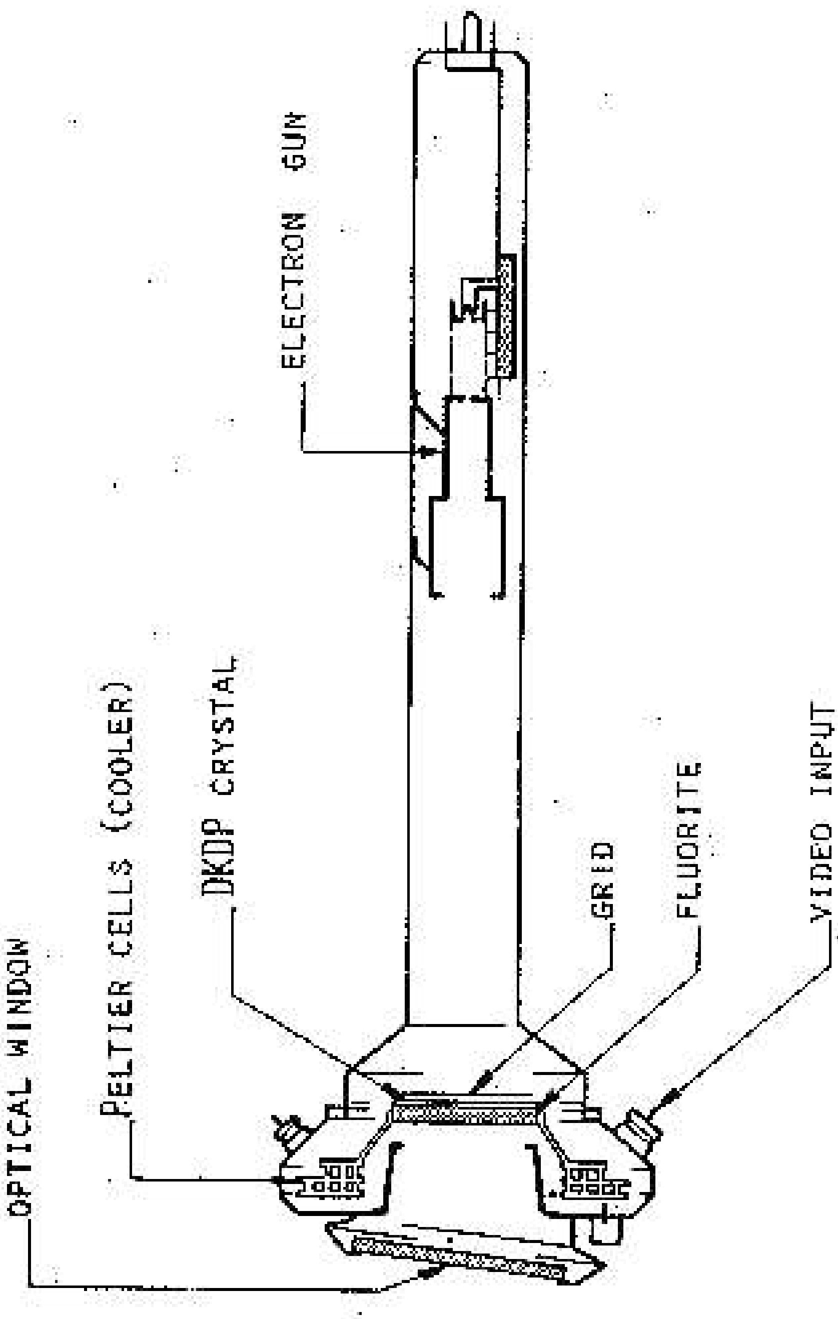


FIGURE 5.26 TITUS LIGHT VALVE

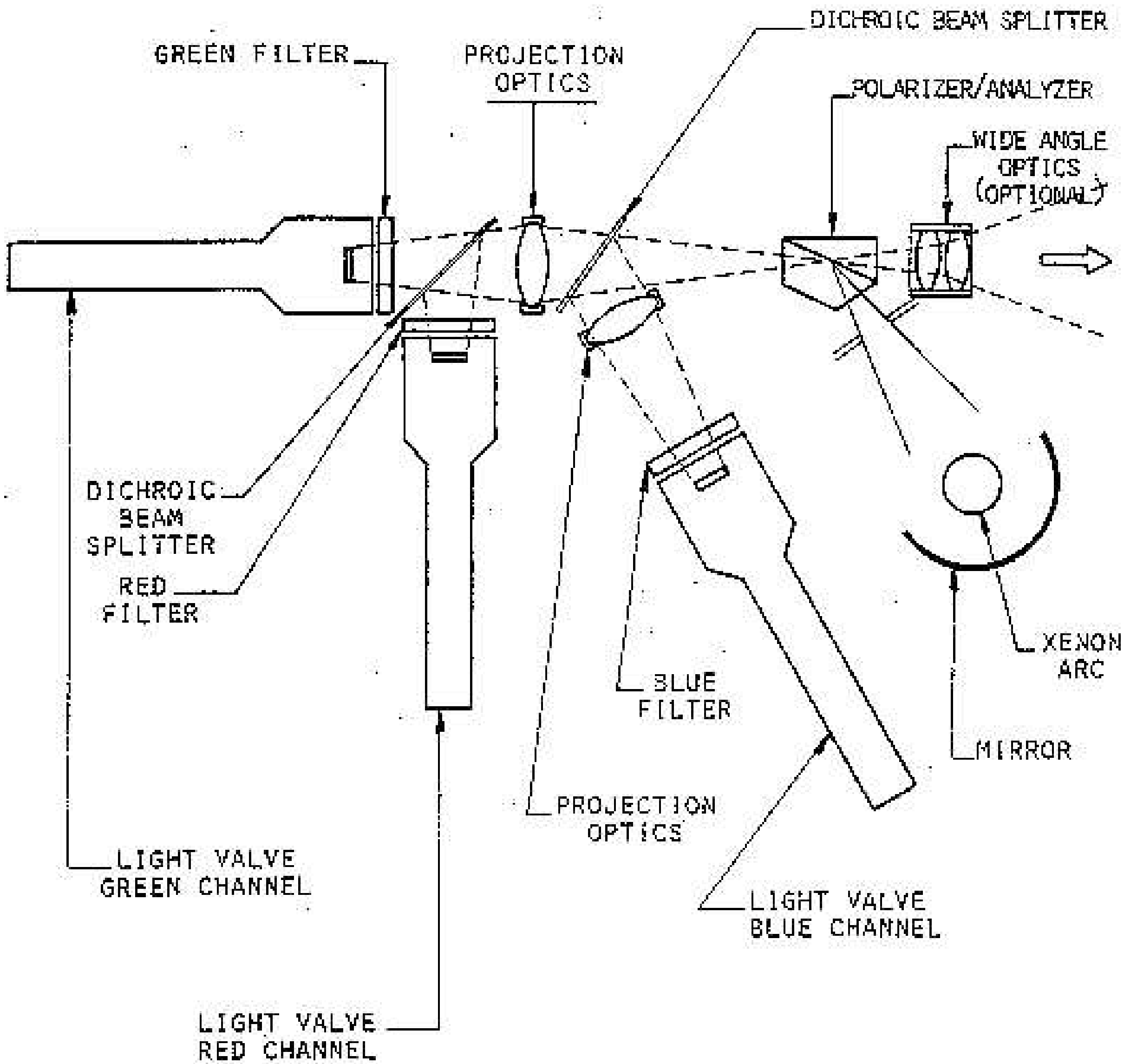


FIGURE 5.27 PROJECTION OPTICS OF SODERN COLOR PROJECTOR

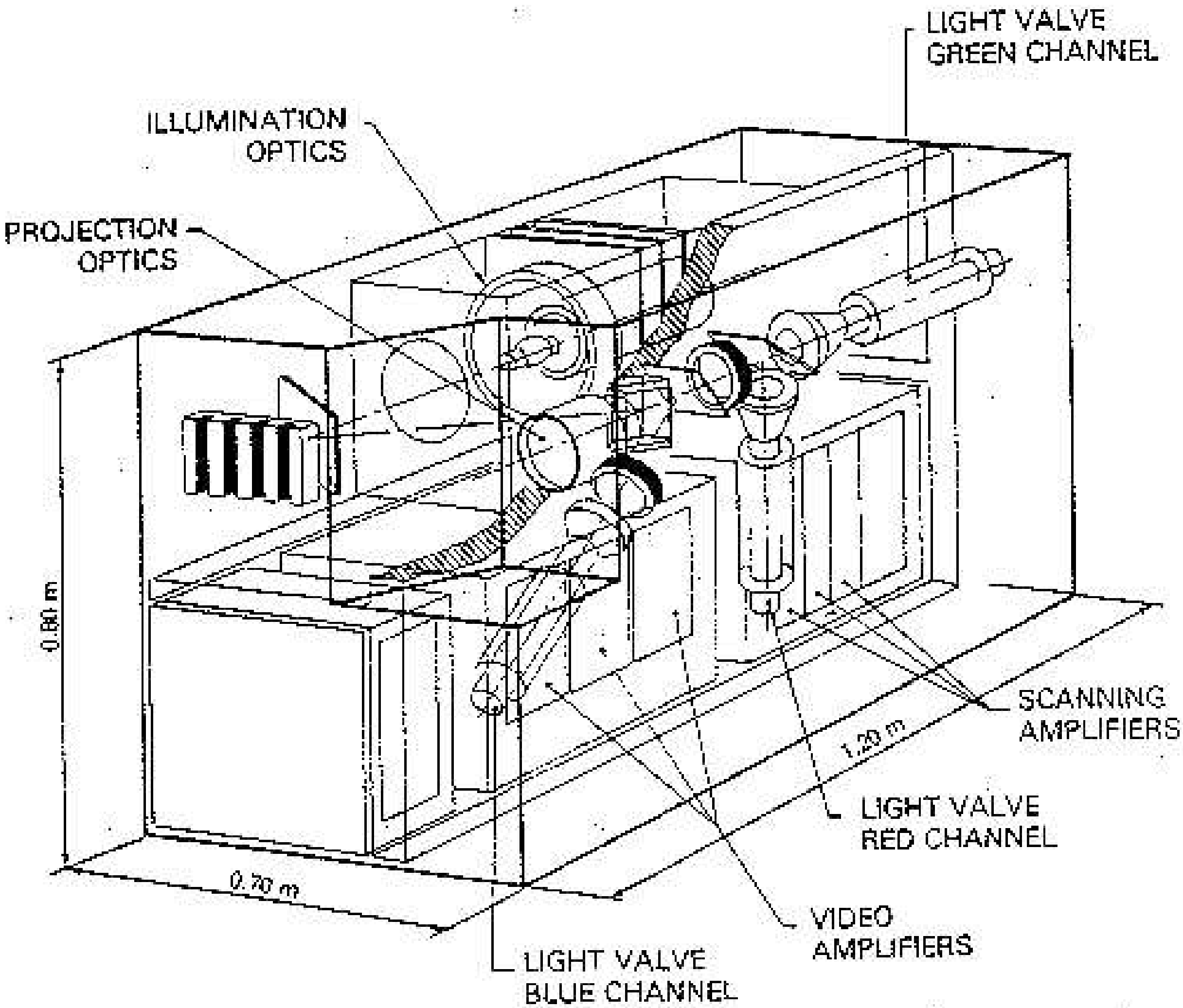


FIGURE 5.28 PROJECTION HEAD OF SODERN COLOR PROJECTOR

Yet another advantage concerns object or image size and its relation to eye relief, this latter term referring to the distance between an observer and closest component of an optical system. Eye relief is important in a flight simulator because it is considered undesirable to have optical components intruding into the cockpit and compromising realism. For example, an object of size 2X, when directly viewed with no intervening optical system, appears to subtend an angle $\Theta\delta$, where:

$$\Theta\delta = 2 * \arctan(x/d)$$

and d is the distance between the object and observer. The "apparent" object size $\Theta\delta$ is seen to be inversely proportional to the distance d. In this situation where no optical system is used, eye relief is equivalent to object distance. Thus, a larger apparent size can be obtained for an object only at the expense of eye relief.

In contrast, if an optical system of focal length f is interposed between object and observer, then a collimated image of the object can be generated in which the angular (or apparent) size Θc is only a function of the actual object size 2X and the focal length f; i.e.,

$$\Theta c = 2 * \arctan(x/f)$$

where it is assumed that the object lies in the back focal plane of the optical system. Eye relief is now independent of viewing distance d, as is apparent object size. The observer can also move longitudinally with no effect on apparent object size.

Thus, a virtual image system can present a "collimated" image in which:

1. Lateral motion has no effect on the angular position of an object,

2. Longitudinal motion has no effect on the apparent size of an object, and

3. For an object having a given apparent size, eye relief can be larger than that obtainable by directly viewing the object.

These systems have traditionally been well received and extensively used in both commercial and military fixed-wing aircraft simulators. Certainly a major part of their appeal has been the belief that since objects are generally viewed from afar when flying an aircraft, that training will be enhanced in the simulator if objects are made to appear at near-infinite distances. Interestingly enough, more recent applications involving rotorcraft have met with some difficulty. For example, a helicopter pilot can get much closer to objects (including the ground) than a fixed-wing aircraft pilot, especially during important training tasks such as take-off, landing, and hover. Because a dearth of motion cues exist at these times, the pilot becomes more susceptible to other visual cues. Many CGI systems do not support a wealth of ground or object detail, so a situation arises where accommodation and optical convergence play an important role. The result in a collimated system is that the pilot perceives objects as being farther away than they actually are. The problem this creates in a training environment is serious, and if carried over into actual practice is disastrous. Fortunately, such optical systems can generally be modified or constrained to attenuate this "negative cueing" effect.

One may recall that real image systems, as previously defined in Section 4.0 and used here, are those that have the observer viewing a surface containing a light-emitting focused image. Generally this surface will be either the faceplate of a CRT or a projection screen. The main advantage of a real image system is that a multi-component optical system for collimation is not usually required. This absence pays dividends in terms of brightness, contrast, and resolution; all of these benefit from encountering fewer optical elements. And because of the relative simplicity, cost is usually less for a real image system.

The disadvantage of a real image system is that it does not have the advantages of the virtual systems. To see where this leads, consider the problem of viewing an image that is close to the pilot. Not only does eye relief potentially become a problem, but negative cueing can arise due to forced eye convergence (noncollimation) during most of a training exercise. Furthermore, head movement will cause an object's angular position or apparent size to change. The obvious solution, of course, is to move the display device or screen as far from the cockpit as possible. This leads to inordinately large CRT's or screens and the need to occupy large amounts of floor space. A size increase, however, is not always possible owing to limitations imposed by either room size or motion platform size. In addition, image brightness will decrease as the square of any increase in viewing distance.

Another problem arising from an increased viewing distance is that having separate displays for both captain and first officer is no longer possible; rather, both will view the same image. This can be a problem when performing many training tasks since correct geometric perspective cannot be presented to both crew members simultaneously. An example is the landing task. When the captain is lined up with the runway centerline, it will appear to the first officer that the aircraft is actually too far to the left. Presumably the first officer would eventually just get used to this artifact; however, it constitutes "negative training" which can prove hazardous if inadvertently carried over to actual flying of the aircraft. In practice, the solution is to avoid using real image systems when two or more members of the flight deck must be trained at the same time. Alternatively, if only one person is actively flying the aircraft and the other members are only passively or occasionally interested in the out-of-the-window visual presentation, then a real image system may prove suitable. Examples include fighter aircraft in which the pilot flys heads-up and the weapons officer is generally flying heads-down with sensors.

6.2 Virtual Image Systems - Beamsplitter/Mirror

One of the commonest and most straightforward virtual image systems is the folded beamsplitter/mirror (BS/M) system that was introduced in Section 4.3 and is illustrated in **Figure 6.1**. When a 25-inch CRT is used as the display input device, a 60-inch radius mirror yields a 30° x 40° FOV; a 50-inch radius mirror yields a 36° x 48° FOV. Recall that larger FOV's are generally not obtainable using a 25-inch CRT with a smaller radius mirror since placement of the CRT closer to the smaller mirror will result in the CRT structure obscuring part of the FOV. **Figure 6.2** illustrates the placement of a BS/M display system on the front of a simulator cockpit. Note that the virtual image display provides sufficient eye relief (here, distance from eyepoint to beamsplitter) so that no part of the optical system intrudes into the cockpit.

If a FOV larger than 36° x 48° is required while continuing to use a BS/M system, then either a larger display input device must be used or several BS/M systems must be mosaicked together. The former alternative is normally not viable due to the unavailability of high performance CRT's larger than 25 inches. The second scheme is the one of choice. Two or more BS/M systems are typically arranged horizontally about the cockpit to provide the wider (and more realistic) FOV. **Figure 6.3** illustrates how such a system looks from the inside of the cockpit. As drawn, the captain can view three displays that afford him a view through the front, left quarter, and left side windows. The first officer has two displays corresponding to the front and right quarter windows.

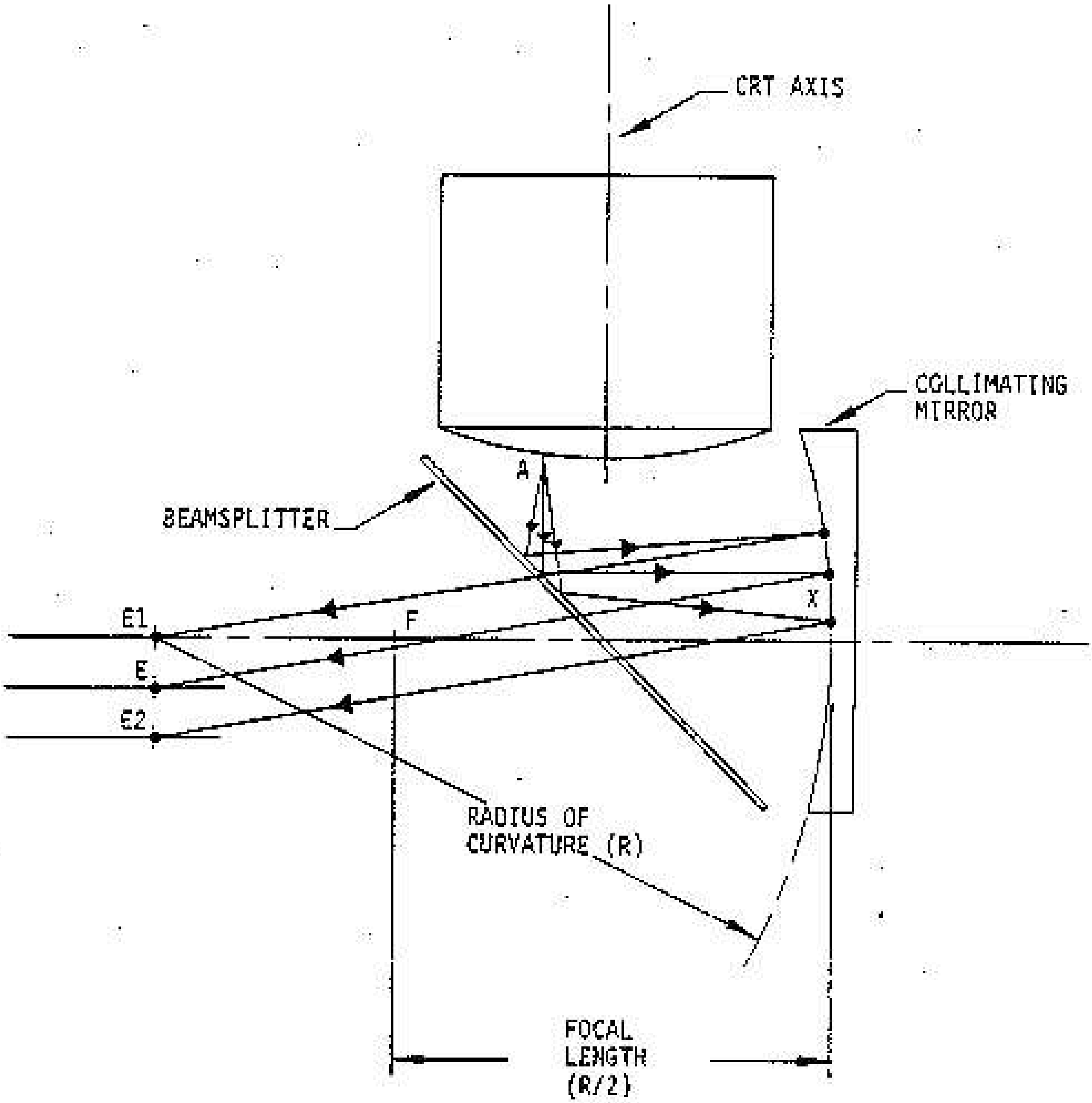


FIGURE 6.1 FOLDED BEAMSPLITTER/MIRROR VIRTUAL IMAGE SYSTEM

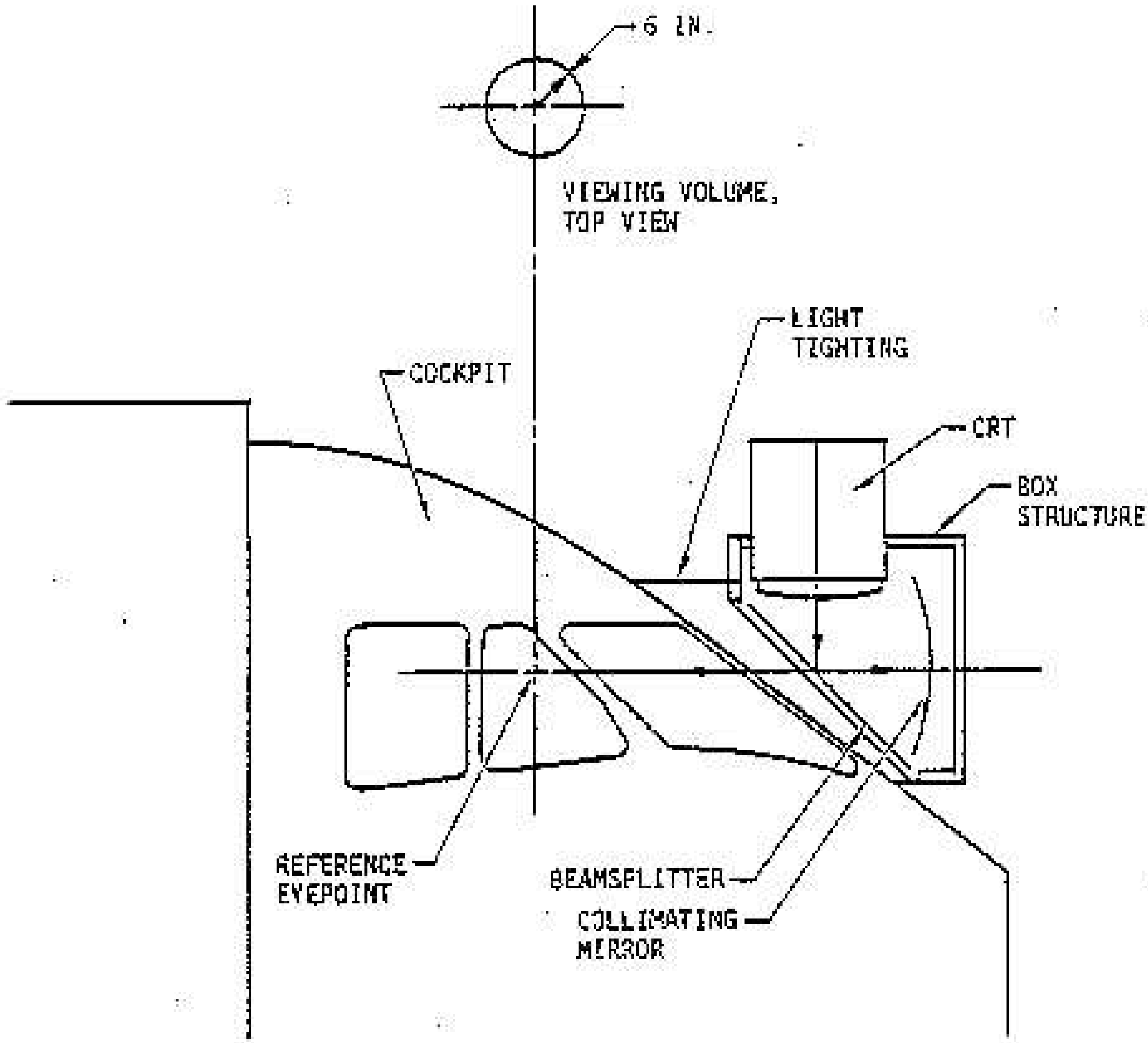


FIGURE 6.2   BS/M DISPLAY ON SIMULATOR COCKPIT

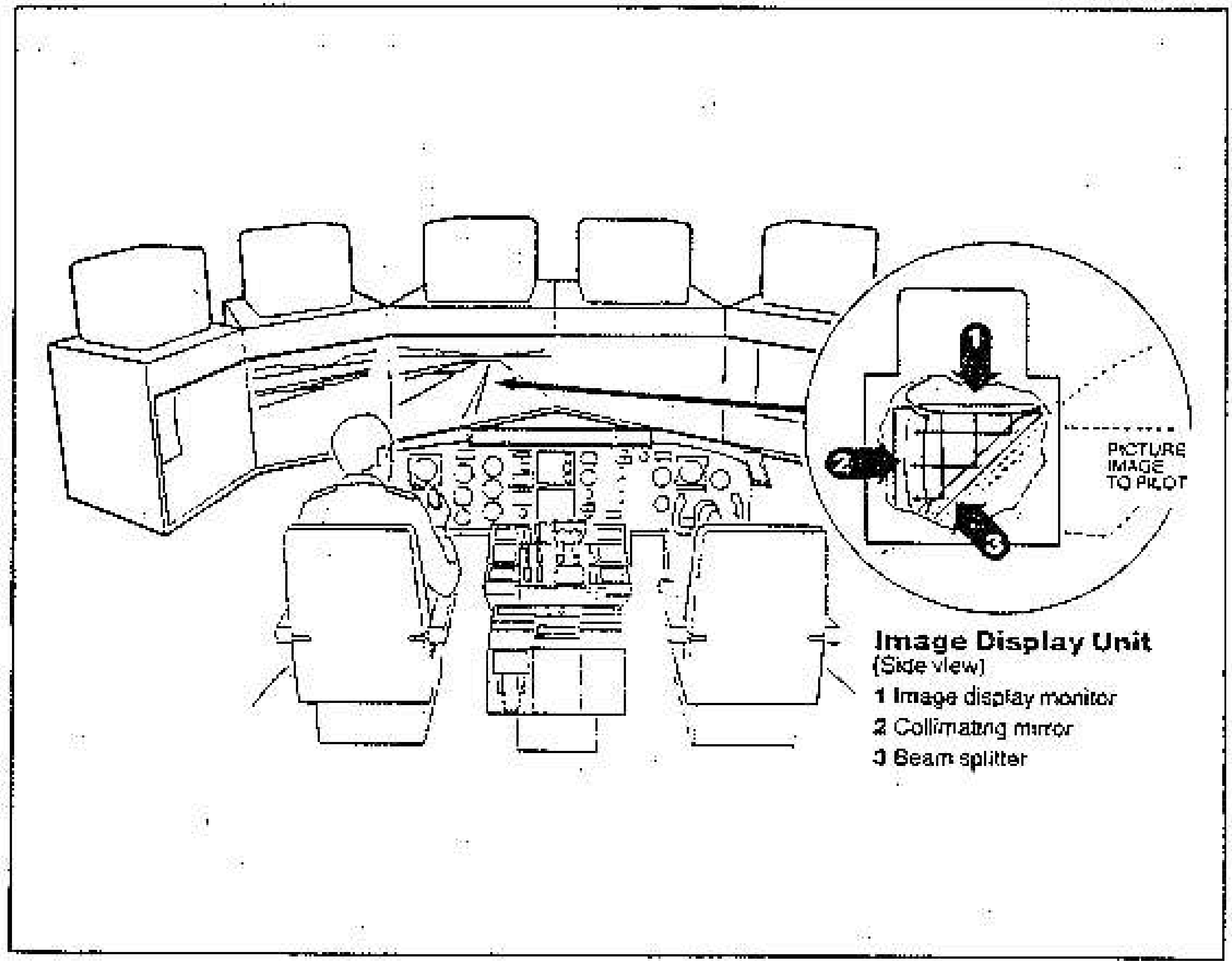


FIGURE 6.3 MOSAICKED BS/N SYSTEM AS SEEN FROM FLIGHT DECK

Often the individual BS/M systems are separated by narrow gaps to minimize packaging difficulties. In some instances adjacent collimated images are overlapped by about 5° to provide the appearance of a continuous image. Such a system is called a "juxtaposed" system. A flight simulator with multiple BS/M windows looks similar to the drawing in **Figure 6.4**.

Because of the limited viewing volume (i.e., eye box) provided by the BS/M system, the captain can not view imagery provided by the first officer's displays, and vice versa. This is a detriment in certain flight tasks. For example, in the base leg of a landing approach, the runway is off the right side of the aircraft, as illustrated in **Figure 6.5**. Because the captain cannot see imagery in the first officer's displays, the runway will be outside the FOV of the captain during a large portion of the particular training exercise. The solution in this case is simply to limit training exercises to situations where the base leg is flown with the runway on the captain's side of the aircraft.

Another problem involves the number of display devices. Except for the two front windows that provide identical imagery to the captain and first officer, each window (i.e., CRT and BS/M combination) requires a separate IG computational channel to provide it with perspectively-correct imagery. Overall simulator cost quickly escalates when additional FOV implies both added displays and added IG channels. A commonly used solution is illustrated in **Figure 6.6** for a four-window configuration. The top figure shows that three IG channels are needed to operate the four windows simultaneously, thus providing both captain and first officer the same size FOV. The bottom figure shows a switching arrangement requiring only two IG channels. Both trainees always have imagery for the front window; however, only one quarter window may be used at a time. Depending on the particular ongoing activity within a training exercise, the IG channel can be dynamically switched between captain and first officer so as to optimize training value.

To summarize, a BS/M virtual image system produces a collimated image which is insensitive to small head movement either laterally or longitudinally. FOV per window is limited in practice to about 36° vertically x 48° horizontally; larger FOVs require multiple windows and additional IG channels. Windows cannot be shared by the flight crew owing to the restricted viewing volume of each window. In terms of overall optical performance, the BS/M is good at not further degrading the resolution of the display input device. Brightness, however, is attenuated by roughly 80%.

6.3 Virtual Image Systems—Off-Axis

An alternative to the BS/M concept is the off-axis virtual image system. It was illustrated previously (see **Figure 4.11**) using a CRT off-axis to a mirror, making a beamsplitter unnecessary. In practice, the system is scaled up, made possible by substituting a projector and rear projection screen for the CRT, as shown in **Figure 6.7**. The pilot looks into a large mirror that collimates the image produced on the rear projection screen. If the screen has a low-gain dispersive coating, then a projected image can be viewed from all parts of the flight deck.

Though a single channel system is easily implemented, the standard configuration uses three projectors crossfiring onto a large rear projection screen. **Figure 6.8** shows this for a Rediffusion system. Termed WIDE (Wide-angle Infinity Display Equipment), the system provides a FOV of 40° V x 150° H; vertical FOV can be biased either as –25°/+15°, –20°/+20°, or –15°/+25° to accommodate different aircraft and training requirements. Also available is a five projector version termed WIDE II that provides a FOV of 40° V x 200° H. In both versions the large spherical mirror, rather than being fabricated from glass and weighing nearly 2,000 pounds, is made by applying a vacuum to the rear surface of a large sheet of aluminized mylar. If the sheet is made to conform to a spherical supporting edge, then the Laws of Physics guarantee a spherical mirror will be produced. In fact, the result is a mirror of good quality that is both inexpensive and lightweight, the latter being especially important since these displays often must be moved about on a motion platform. A photograph of a WIDE system on a flight simulator is shown in **Figure 6.9**.

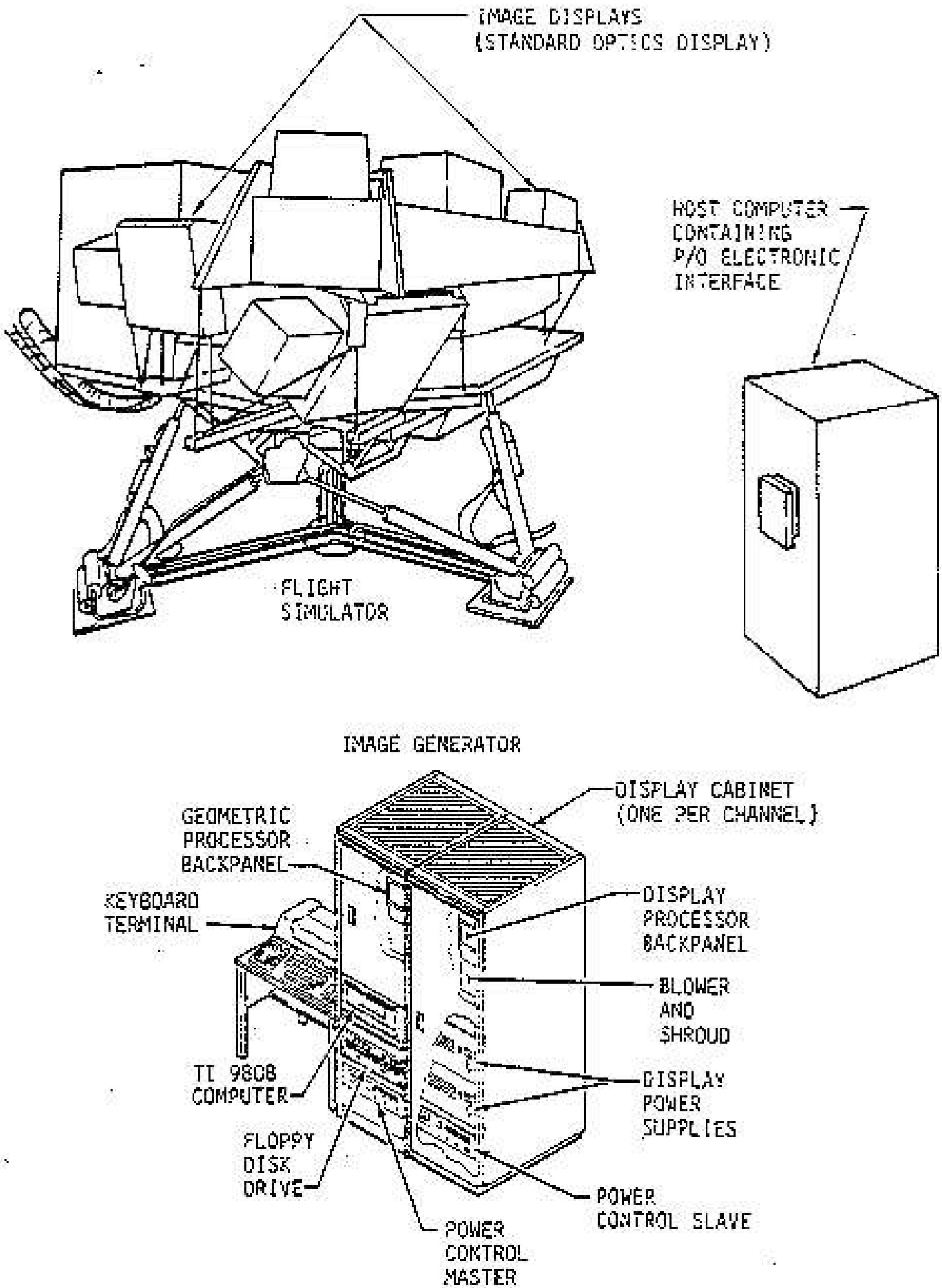


FIGURE 6.4 MOSAICKED BS/M SYSTEM AS SEEN FROM THE OUTSIDE

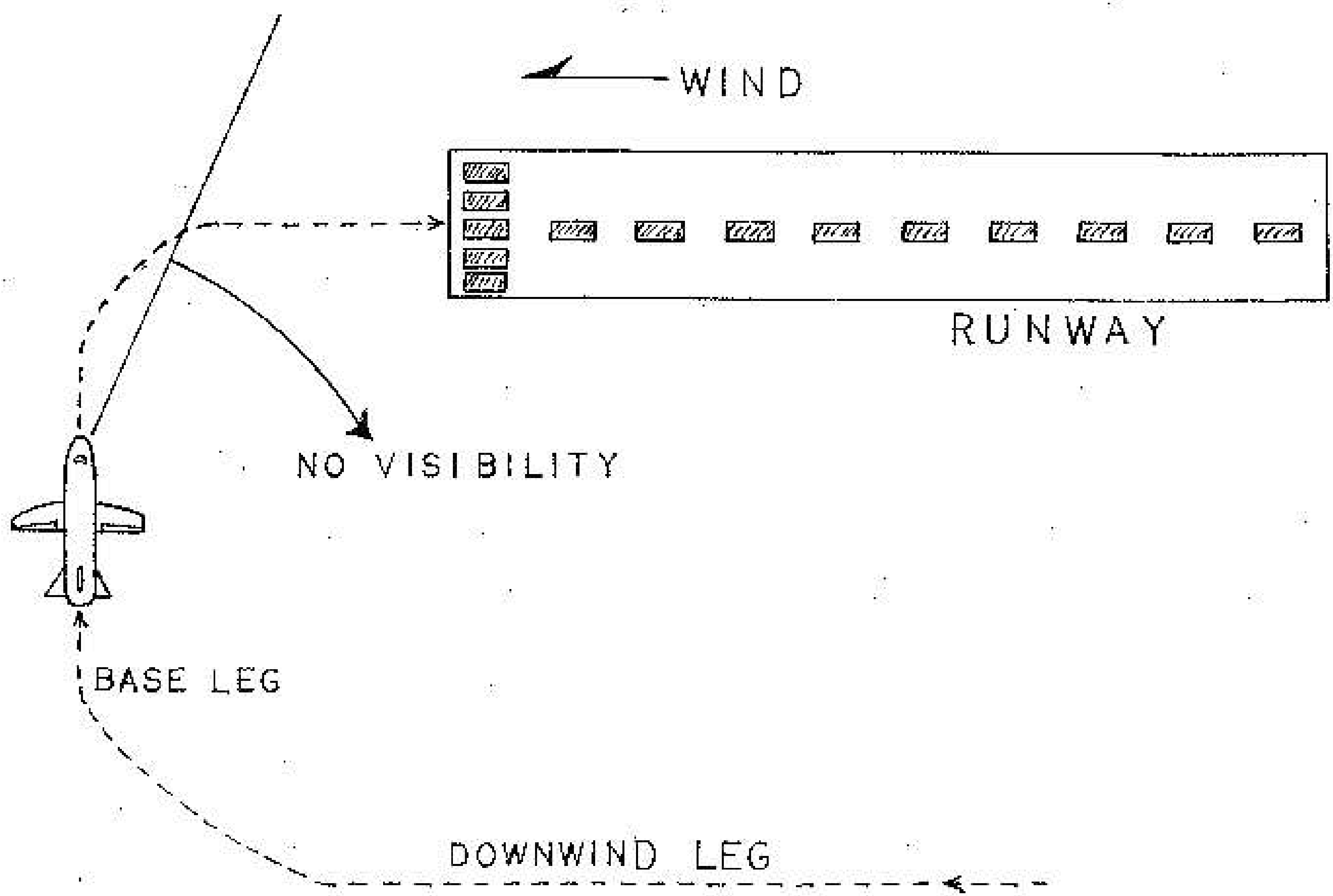


FIGURE 6.5 BASE LEG OF APPROACH FOR A RUNWAY OFF TO THE RIGHT

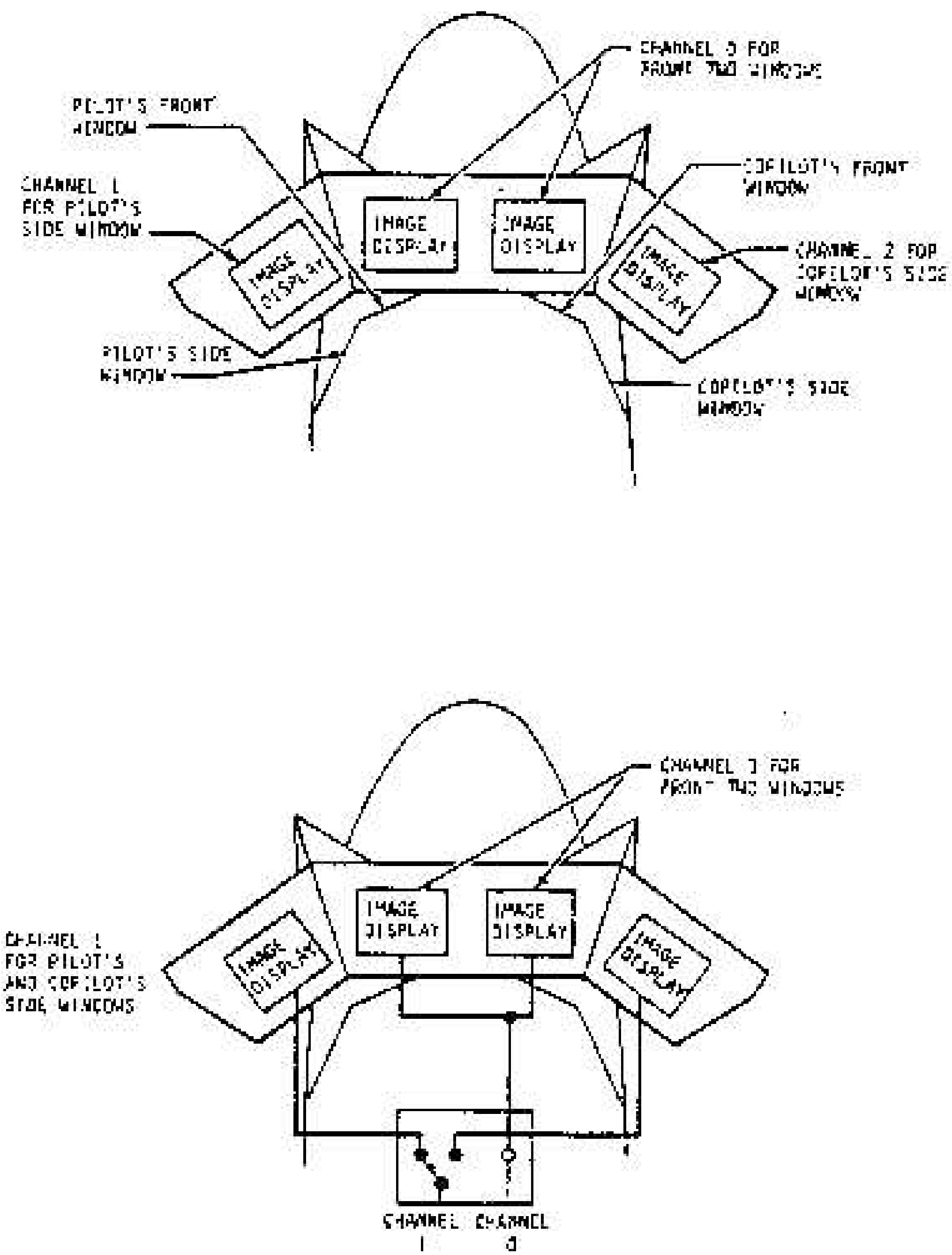


FIGURE 6.6 FOUR WINDOW BS/M SYSTEM WITH EITHER 2 OR 3 CHANNELS

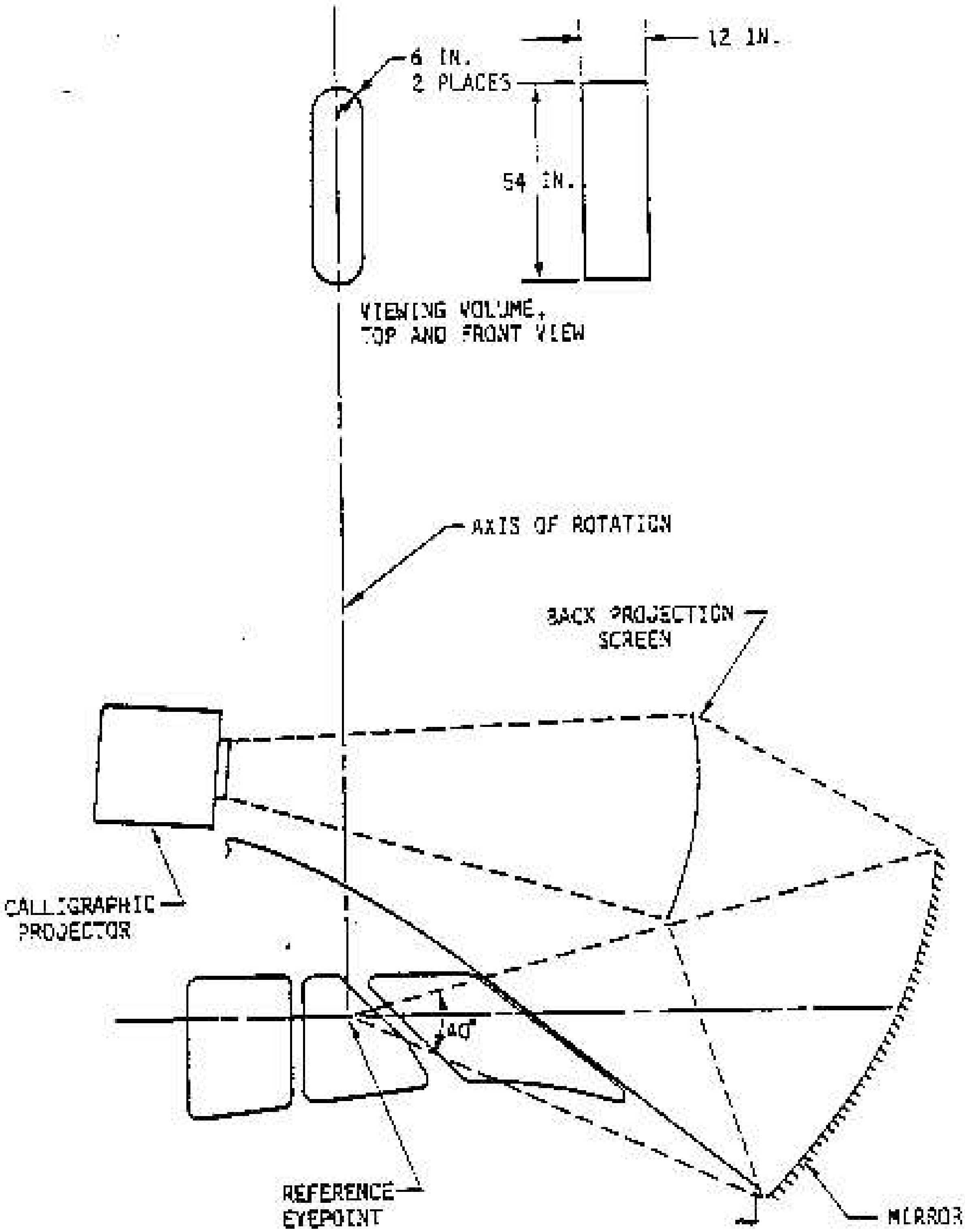


FIGURE 6.7 OFF-AXIS VIRTUAL IMAGE SYSTEM USING A PROJECTOR

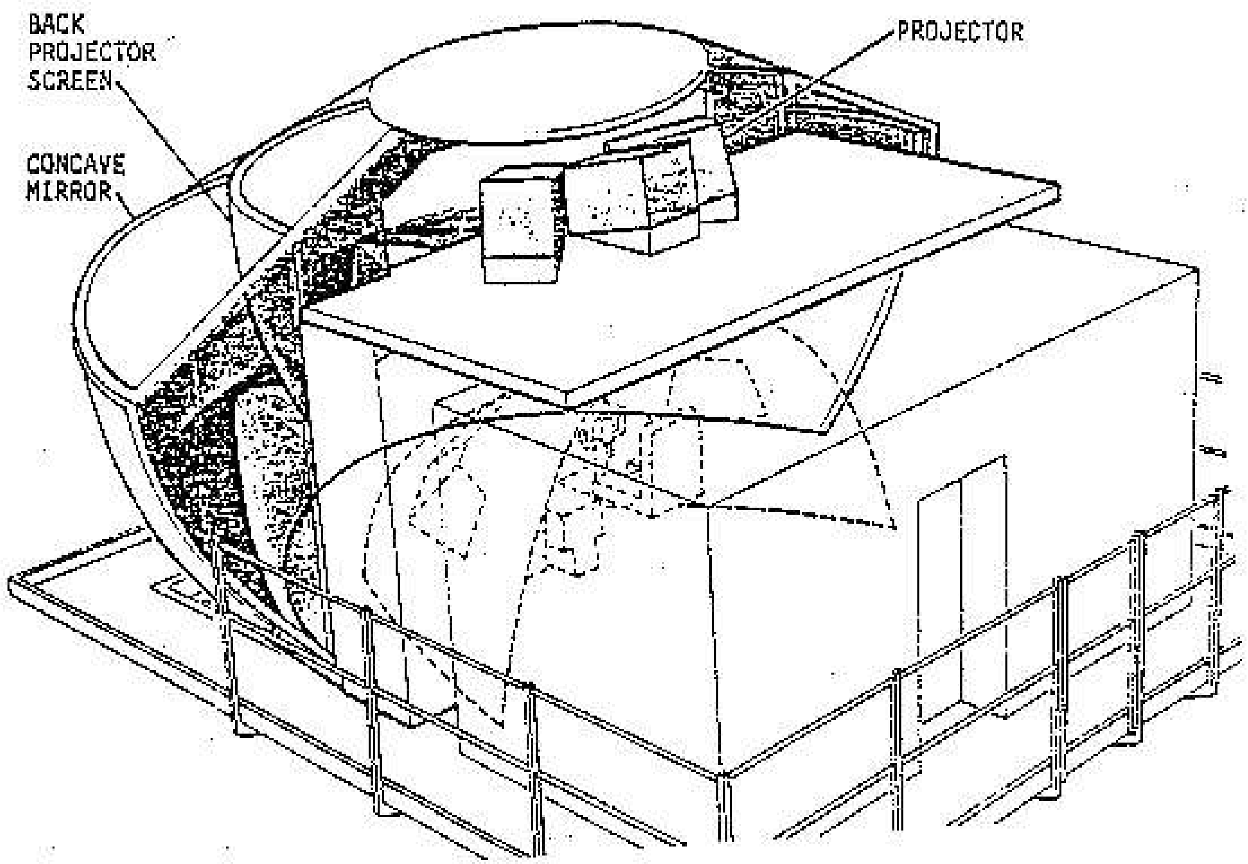


FIGURE 6.8 WIDE

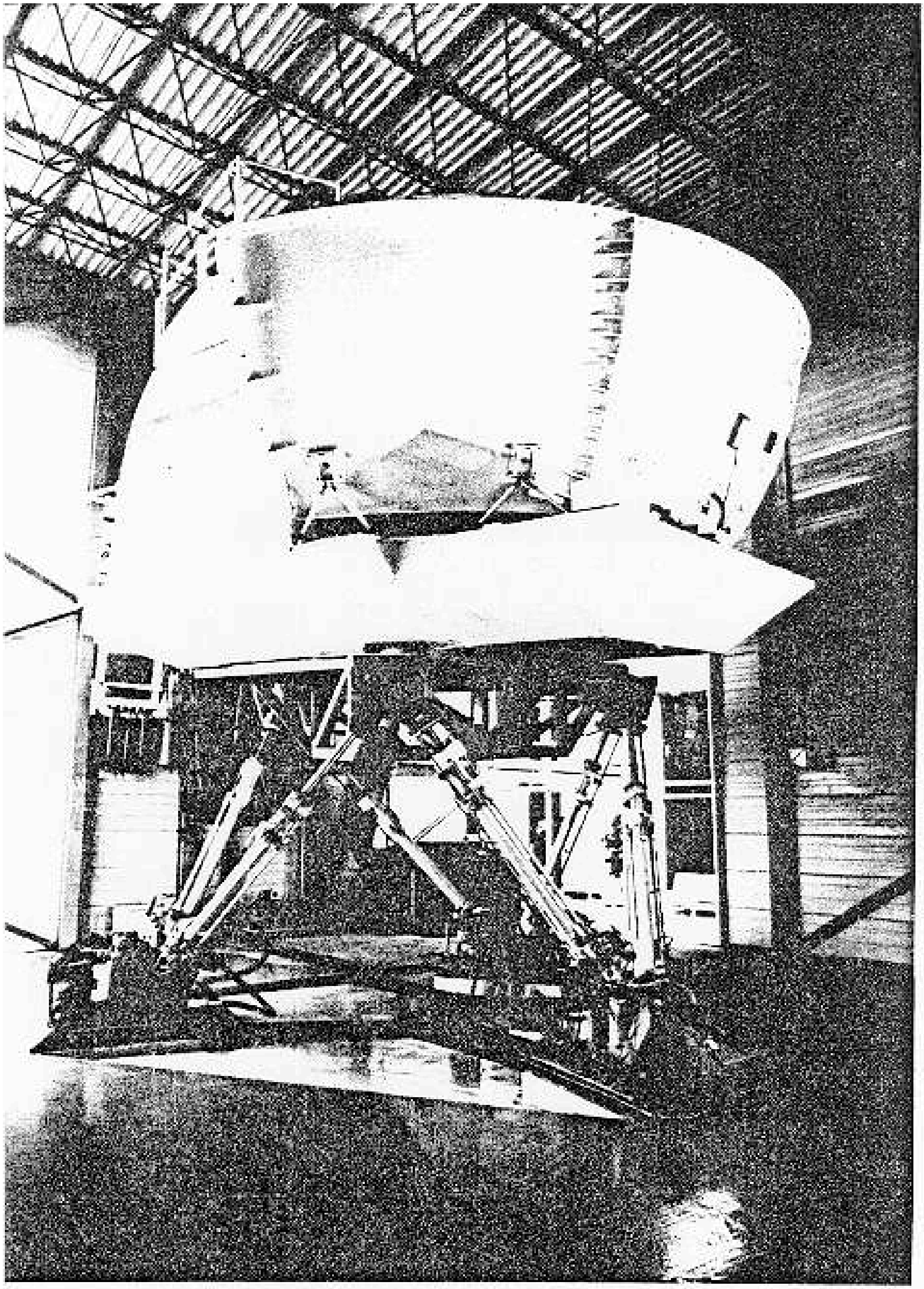


FIGURE 6.9 PHOTOGRAPH OF WIDE ON A MOTION SYSTEM

To ensure that the displayed imagery appears continuous in an off-axis system, it is necessary to soft edge-match adjacent display channels. The implication here is that adjacent channels of imagery are projected with some overlap onto the rear projection screen in a manner that guarantees a continuous appearance at the join. In a three-channel system such as WIDE, two edge-matches are required. This is accomplished by modifying the video circuitry of the projectors to allow video level at the left and right edges to be ramped up and down, respectively. When properly adjusted, the joins should be nearly invisible. In addition, a good edge-match requires that objects bridging or moving across a join do so in a continuous manner. Thus, the projectors must possess sufficient geometric adjustment to ensure that adjacent channels can be successfully registered at the joins. Calligraphic projectors are especially good at this since linear deflection implies the capability to introduce the wide range of correction terms needed for off-axis projection onto a spherical screen.

The major advantage of an off-axis system such as WIDE is that all portions of the FOV are visible to all parts of the flight deck. This means that a flight engineer can take part more fully in a training exercise. More important, the captain has a cross-cockpit view out of the right side windows, and the first officer has a comparable view out of the left side windows. This permits a greater number of tasks to be trained on the simulator; e.g., flying the base leg of a landing approaching in which the runway is on the right side of the aircraft. Furthermore, because a larger instantaneous FOV is provided to the trainee, more visual cues are available to the trainee on which to base control decisions. For example, since peripheral vision is very sensitive to motion cues, the wider FOV allows the trainee to judge aircraft velocity more accurately.

There is a price to be paid, however, for the wide FOV afforded by the off-axis system. Brightness tends to be less than with a BS/M system since the light energy available for viewing the image is spread over a larger viewing volume. Resolution can also suffer because of scattering within the low-gain rear projection screen.

In comparing the BS/M and off-axis virtual image systems, it is interesting to note that future BS/M development is largely dependent on the production of larger and better color CRT's. Because there are only a few shadow mask CRT manufacturers (such as RCA, Matsushita, Mitsubishi, and Sony) and these are driven principally by the consumer market, progress relevant to simulators appears tied to such consumer interests as high-definition TV. In contrast, development of off-axis imaging systems is largely tied to CRT projection tube and phosphor improvements. Because a projection tube is a simpler device than a shadow mask tube, more companies are involved in its manufacture. Both of these facts enhance the liklihood of additional improvements occuring in the near term. As a result, it is expected that the use of projection systems will dramatically increase over the next several years.

6.4 Virtual Image Systems—PANCAKE™ Window

In some applications, such as air-to-air combat simulation, both horizontal and vertical wide FOV's are required for effective training. If a collimated system is specified as well, then a mosaicking of virtual image systems is needed. Generally BS/M systems are unsuitable because they are too bulky, too restrictive in FOV, and often too limited in eye relief. Mosaicking off-axis systems both horizontally and vertically, on the other hand, is next to impossible. One solution that was developed by Farrand Optical Company about 15 years ago is the PANCAKE Window, so called owing to its minimal thickness and, therefore, relatively flat appearance.

Figure 6.10 illustrates the optical components comprising of the PANCAKE Window. One underlying principle is that vertically polarized light will be converted to circular, horizontal, circular, and then vertical polarization after one, two, three, and four passes through a quarter-wave plate, respectively. As shown, unpolarized input light is first vertically polarized. It next passes through a spherical beamsplitter mirror, followed by a quarter-wave plate to yield circularly polarized light. The light is then incident on a plane beamsplitter mirror which then passes through a quarter-wave plate, plane beamsplitter mirror, and a second quarter-wave plate. This light, having passed through a quarter-wave plate two additional times, is now vertically polarized again, thus allowing it to successfully pass through a final vertical polarizer. Any other light making it to the final polarizer will have passed through a quarter-wave plate only twice and will be horizontally polarized. This unwanted light is absorbed by the vertical output polarizer, thus guaranteeing that an observer sees only the collimated image. It should be noted that the spherical input surface to the PANCAKE should be positioned at the focal plane of the spherical beamsplitter mirror; i.e., such that $x + 2s = R/2$ as defined by the lower drawing in **Figure 6.10**.

A typical PANCAKE using a 48-inch radius spherical beamsplitter mirror is less than twelve inches thick. An 84° diagonal FOV yields an image with 4:3 aspect that is roughly 68° x 51°. Eye relief is 37 inches, and 12 inches of head motion is permitted about the design eyepoint located at the center of curvature of the mirror. The only significant aberration is spherical aberration; otherwise, the entire FOV is relatively free of color fringing and geometric distortion. Maximum decollimation is no larger than 0.037 Diopters; i.e., objects appear no closer than 87 feet.

The PANCAKE provides a virtual image of good overall optical quality; however, some artifacts do exist. Though bleed-through of an uncollimated source image is theoretically not possible, some unwanted light does make it to the observer. This is particularly noticeable in scenes having high contrast, such as stars against a dark sky. A solution used on the NASA Space Shuttle Simulator was to manufacture a special tilted PANCAKE (rather than the typical in-line arrangement) which directed collimated light to the observer while uncollimated light exited the window in a direction that bypassed the viewing volume.

A more significant problem with the PANCAKE is light loss on passing through the window. For a typical unpolarized input image, only 3% of the light can theoretically reach the observer. In practice, scattering and material losses reduce this transmission figure to about 1%. Even assuming that a polarized input source can be utilized, transmission efficiency only rises to 2%. As a consequence, the PANCAKE Window has principally been used with either a light valve projector and screen or with a monochrome CRT. A color CRT is not generally satisfactory as an input device because the shadow mask only allows about 20% of the electron energy to reach the phosphor; this inefficiency makes it significantly less bright than a comparable monochrome CRT.

Figure 6.11 illustrates one of the first simulators to incorporate the PANCAKE Window. The Advanced Simulator for Pilot Training (ASPT) at Williams AFB consists of two cockpits mounted on six-degrees-of-freedom motion platforms. Each cockpit is surrounded by seven PANCAKE displays mounted in a dodecahedron structure and arranged to provide a 300° horizontal x 140° vertical FOV to the pilot. The input devices are a mix of light valve projectors and 36-inch monochrome tubes. Brightness is nominally 4 ft.L.; contrast is about 20:1. Driven by an IG producing 1000 raster lines, resolution is 6 arc-minutes.

With a simulator such as the ASPT it is difficult to depict fighter aircraft at distances greater than 3–5 km because the aircraft tends to blink on-and-off as it moves between raster lines. Thus realistic maneuvering as part of air-to-air combat training can only occur at fairly close range. To overcome this handicap, the Air Force built in 1975 the TAC ACES (Tactical Air Command's Air Combat Engagement Simulator) at nearby Luke AFB. Consisting of two cockpits mounted on motion platforms, it is similar to ASPT except that it uses eight PANCAKE displays arranged in a dodecahedron to provide a 300° horizontal x 150° vertical FOV per cockpit. The input screen of

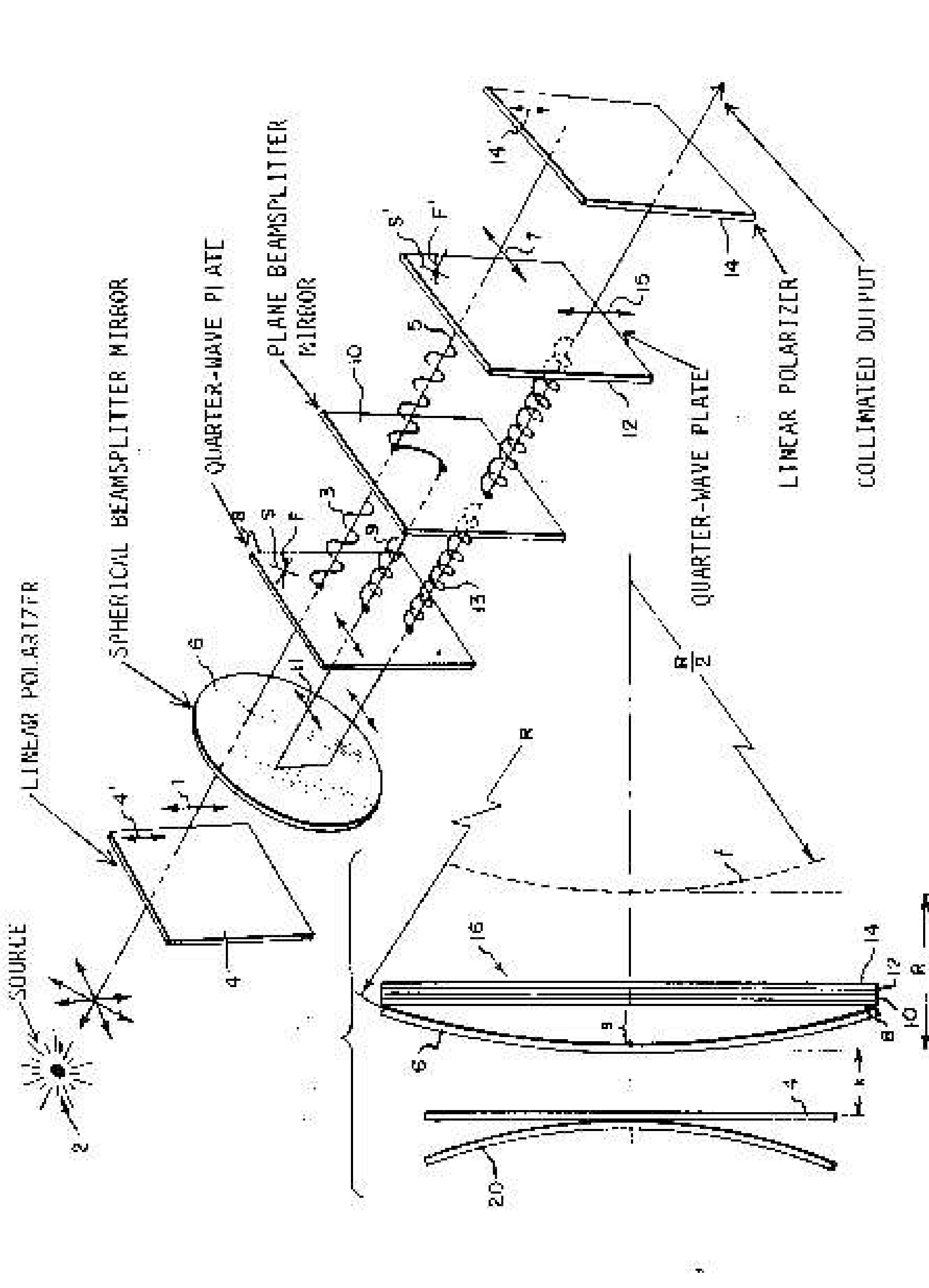
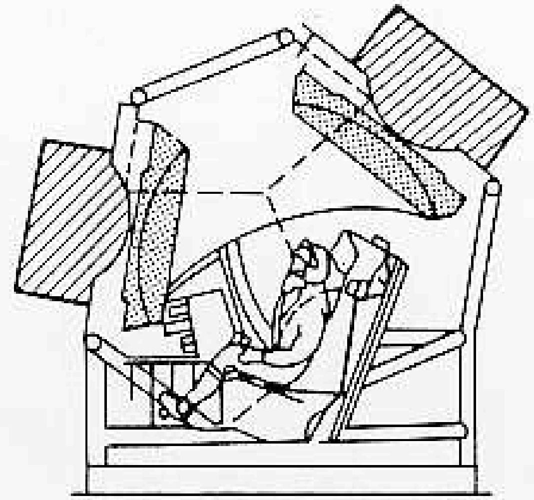


FIGURE 6.10 OPTICAL CONFIGURATION OF PANCAKE WINDOW



IN-LINE INFINITY OPTICS
(ILIOS) WIDE FIELD-OF-VIEW

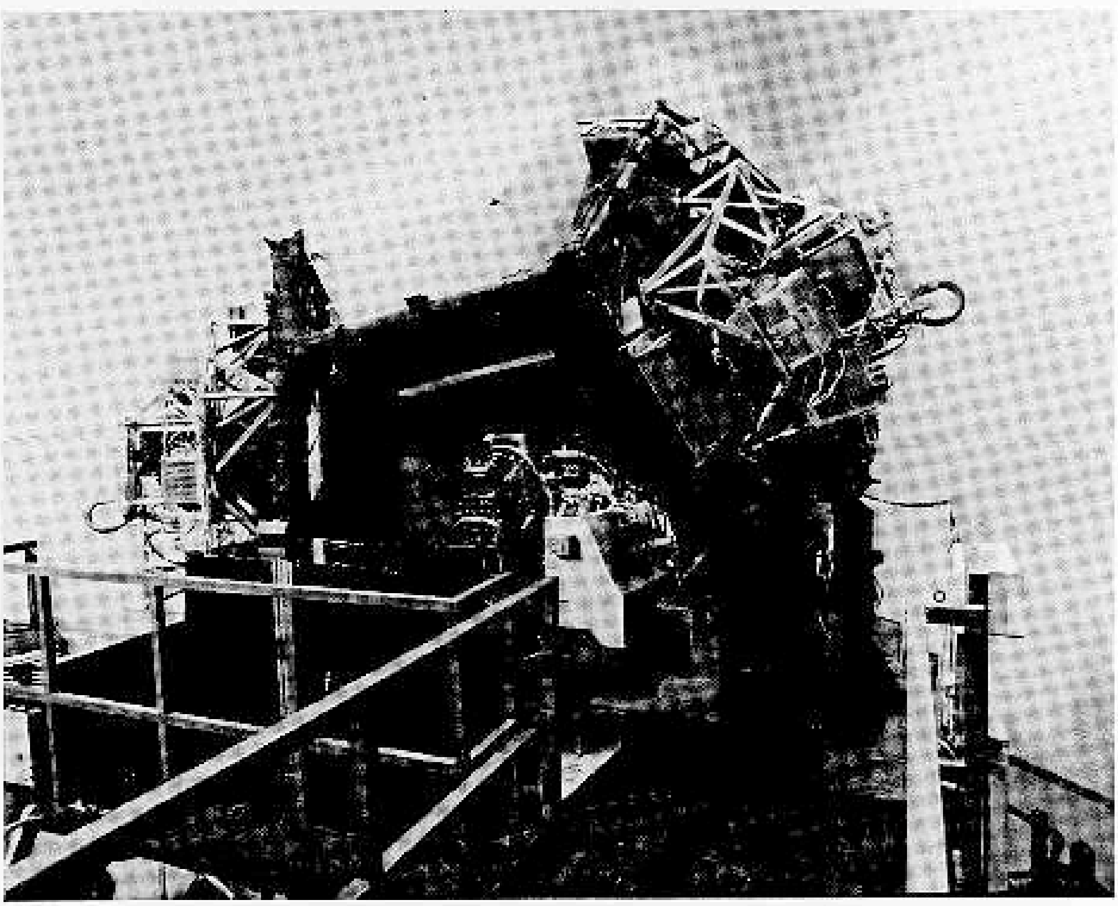


FIGURE 6.11 ASPT

each PANCAKE is a 27-inch monochrome CRT with a special attribute: the two interlaced fields consist of a full raster scan of low resolution alternating with a mini-raster containing the high-resolution image of an enemy aircraft. This mini-raster is generated by a TV camera looking at an actual aircraft model and can be positioned anywhere on the face of the CRT; i.e., anywhere in the total FOV. It maintains high resolution by only subtending an angle large enough to display the aircraft. The aircraft model is under computer control and is positioned in front of the camera as a function of how it is being flown by the training instructor or student pilot in the other cockpit. The net effect is that the trainee sees a low-resolution background scene overlayed by a high-resolution image of an aircraft that is visible at distances greater than the 3–5 km available in the ASPT.

6.5 Real Image Systems—LFOV

Nearly all real image systems avoid direct-view monitors in favor of projection technology. **Figure 5.6** illustrated a display in which three projectors produce imagery on three discrete, spherical front projection screens situated in front of a Cessna 421 cockpit. This concept was taken several steps further by producing a LFOV (Limited Field Of View) display system that was used by TAC to evaluate the advantages of placing a visual system on an F-15 cockpit simulator built by Goodyear Aerospace.

Figure 6.12 roughly illustrates the configuration of the LFOV. The cockpit sat inside a 10-foot radius dome. The inside, front portion was smoothed and coated to produce a spherical screen of good quality having a gain of about four. Four RSL Calligraphic Projectors located above and behind the cockpit projected full-color raster imagery onto the coated dome, thus providing a FOV of 160° horizontal x 60° vertical. The horizontal FOV was biased –100°/+60°, but could have been switched to –60°/+100°. The vertical FOV was fixed at –20°/+40°. Soft edge-matching was used to ensure that the entire image appeared continuous. It should be noted that one reason for biasing the horizontal FOV to either left or right is because joins are always somewhat discernible. The bias on an even-numbered channel system ensures that a join does not exist in the area most often used by the pilot; i.e., directly in front of the aircraft.

Brightness of the LFOV system was 3 ft.L; resolution was about 5 arc-minutes per pixel. The level of resolution was suitable for supporting air-to-ground missions, but was inadequate for some air-to-air combat tasks. The lack of a full visual behind the wing-line was also a detriment in practicing defensive fighter maneuvers. This problem was obviated somewhat by complementing the visual with a Laser Spot Projector (LSP) built by Goodyear and located inside the dome near the nose of the aircraft. Whenever the enemy fighter (or specified ground target) left the 160° x 60° FOV, the LSP would take over and allow the pilot to keep track of the whereabouts (but not the attitude) of the enemy aircraft.

6.6 Real Image Systems—WFOV

An example of a Wide Field-Of-View (WFOV) system is Device 2E7, the F/A-18 Weapons Tactics Trainer built by Hughes Aircraft for the U.S. Navy. Its purpose is to provide sufficient visual cues for training both Air Combat Maneuvers (ACM) and air-to-ground weapon; tasks. The system configuration is shown schematically in **Figure 6.13**. Two training stations are provided, with each station consisting of a 40-foot diameter dome containing a replica of an F/A-18 cockpit. The inside surface of the dome is coated with a low-gain material to enable its use as a spherical projection screen. Low resolution background scenes of sky/earth imagery are displayed on the dome using three, color light valve projectors located just outside the dome. Four monochrome projectors placed on the corners of the cockpit allow either air or ground targets to be displayed with high resolution. **Figure 6.14** shows approximately how the seven projectors are positioned about the dome. The result is a FOV coverage of –50°/+90° vertical (140° total) and a full 360° horizontal.

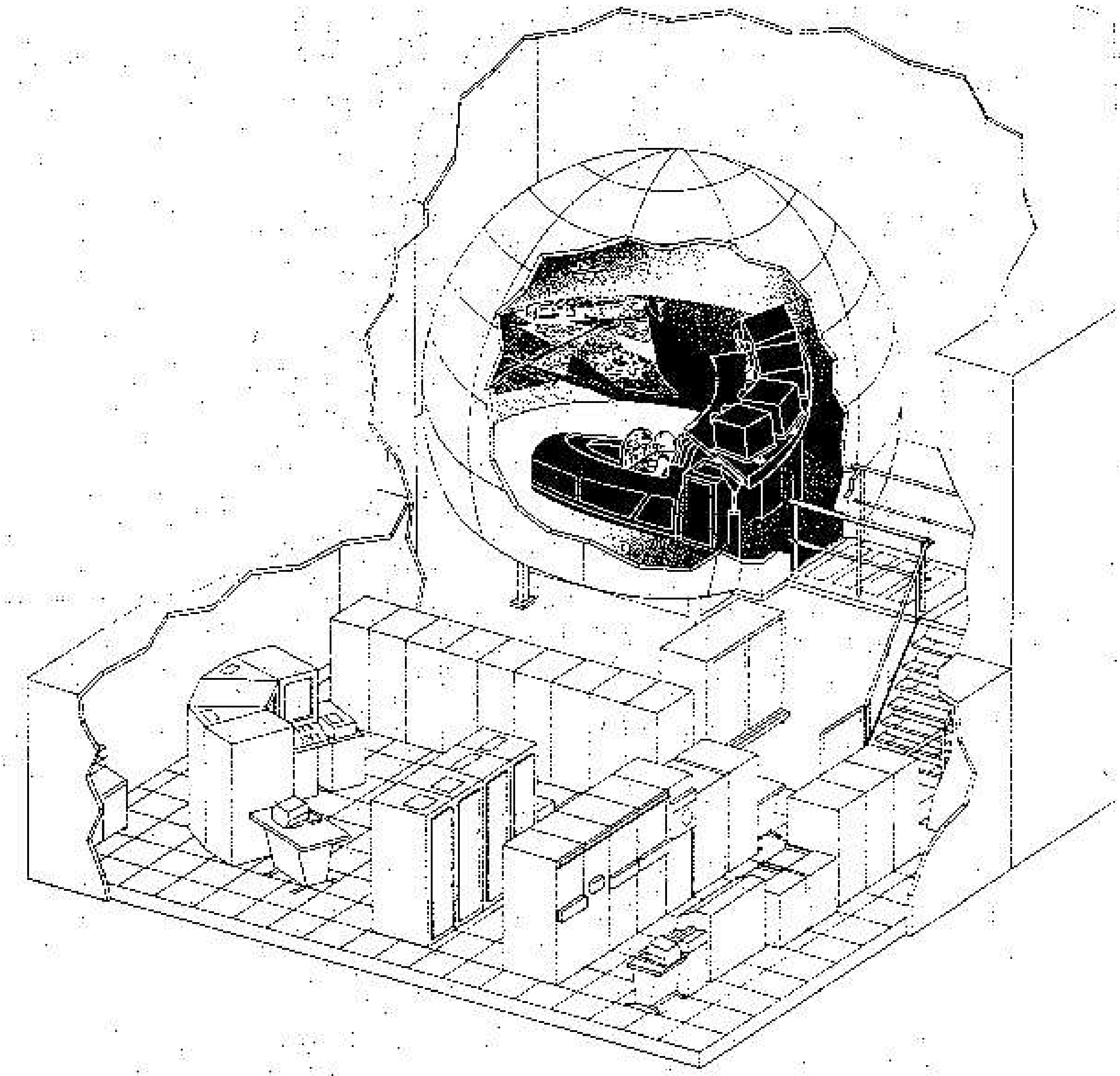


FIGURE 6.12 CONFIGURATION OF LFOV

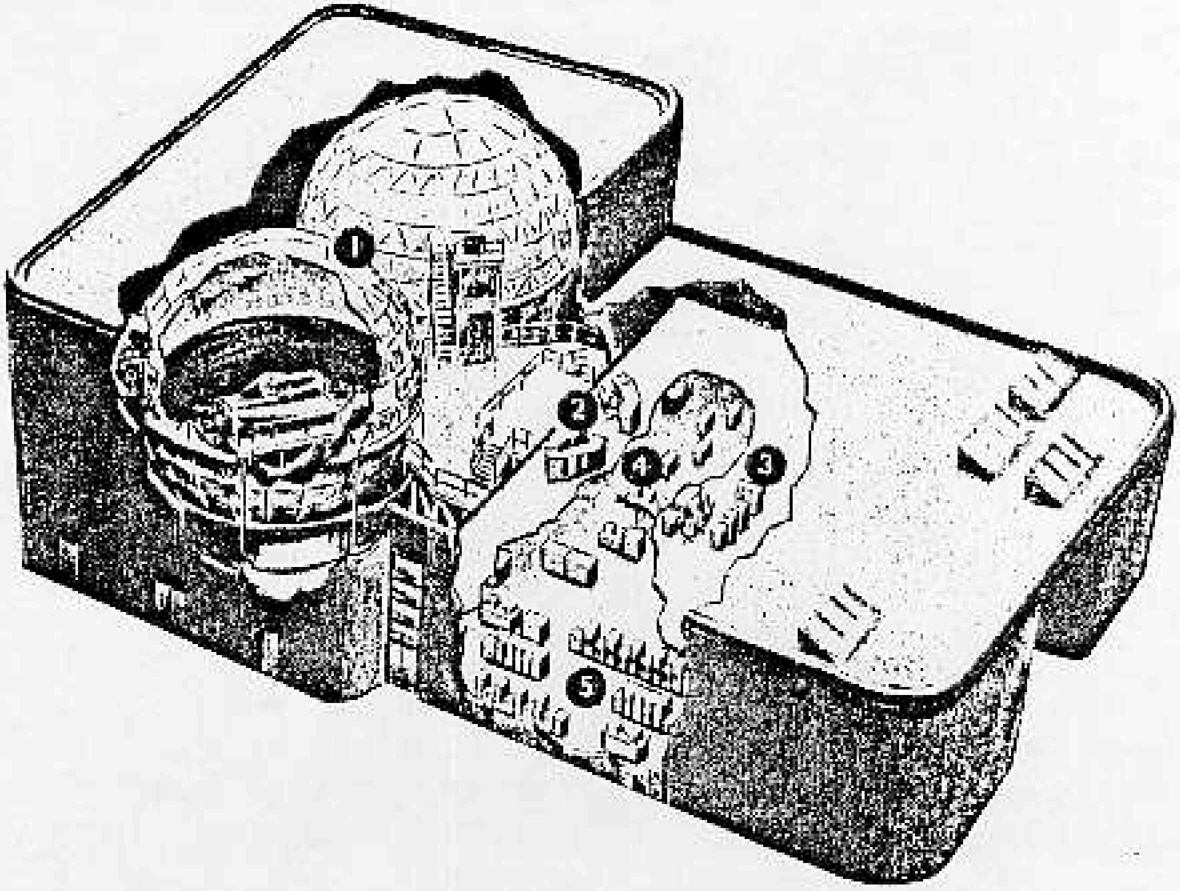


FIGURE 6.13 CONFIGURATION OF F/A-18 WTT

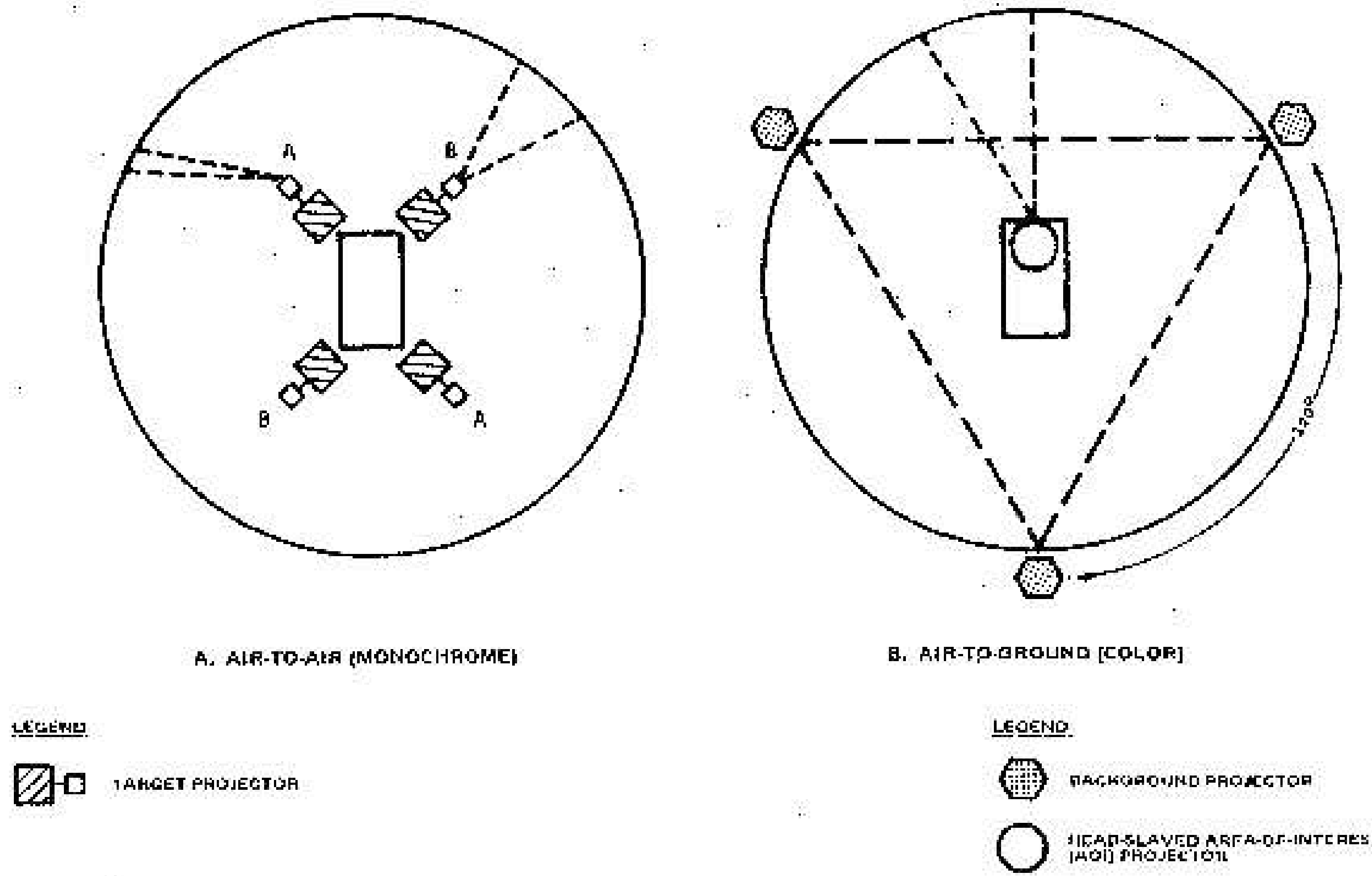


FIGURE 6.14 POSITION OF PROJECTORS ON F/A-18 WTT

The target projector is particularly noteworthy since, like the mini-raster in TAC ACES, it permits a limited number of high resolution objects to be successfully displayed amidst an otherwise low-resolution scene. In device 2E7 two targets can be accommodated, each target requiring two projectors on opposite corners of the cockpit to ensure full coverage of the dome. As shown in **Figure 6.15**, each projector contains a 6-inch diameter CRT having P43 phosphor and capable of high brightness (20,000 ft.L.) and high resolution (3 mil spot). A six-element lens is used to image the CRT faceplate onto the dome. Within the optical train are two servo-driven mirrors for slewing the target image in both azimuth and elevation in response to computer commands arising from target movement. In addition, the CRT itself is mounted in a servo system that moves it longitudinally to ensure good focus at the varying throw distances that result from slewing a projector located off-center in the dome. Brightness and resolution are as high a 2.4 ft.L. and 1 arc-min per line pair, respectively. Additional performance parameters are listed in **Figure 6.16**.

The Sky/Earth background projectors are 500 lumen, full-color GE Light Valve Projectors that project into the dome through special wide-angle lenses providing a 90° cone angle. Since the axis of projection passes through the design eye point located at the center of the dome, each projector is capable of providing 180° of imagery. However, due to some occultation by the cockpit structure, a third projector is required. The projection optics were carefully designed so that no direct illumination is incident at the design eyepoint. Edge-matching is accomplished by overlapping the Sky/Earth displays by about 1° and minimizing brightness discontinuities using shading techniques. Concerning performance, brightness and resolution are 0.1 ft.L. and 36 arc-min per line pair, respectively. Additional performance parameters are listed in **Figure 6.17**.

6.7 Real Image Systems—ACAVS

In 1975 a joint Army/NASA program was formulated to develop a high-fidelity R&D simulator known as the Rotorcraft System Integration Simulator (RSIS). Its task was to establish requirements for rotorcraft (as opposed to fixed wing) simulation and to devise an appropriate implementation strategy. It was decided that motion cueing would be generated by combining a six degree-of-freedom motion platform (contracted to Franklin Laboratory) with the existing Vertical Motion Simulator (VMS) at NASA-Ames. A second portion of the program provided for an interchangeable rotorcraft cab, a development station, and an advanced wide-angle visual system. It is known as the Advanced Cab and Visual Systems (ACAVS) and was developed by American Airlines Training Corp.

Of primary concern here is the visual portion of ACAVS, consisting of a real image projected onto the inside of a 20 foot diameter dome (see **Figure 6.18**). What differentiates this system from other dome systems, however, is the unique opto-mechanical device for image projection. The color computer-generated images from three GE Talaria Projectors are masked, horizontally juxtaposed, and optically blended to form a near-continuous wide-angle image. This composite image is then relayed through slewable optics for projection onto the dome from a single exit pupil located about 1–1/2 feet from the pilot's eye point. Because the functioning of this slewable opto-mechanical assembly is similar to probes used on early model board systems but is operating in reverse, it is termed an EBORP ("PROBE" spelled backwards). FOV is roughly 60° vertically x 136° horizontally. Luminance is in excess of 15 ft.L. Additional performance goals are enumerated in **Figure 6.19**. Note that additional reduction in geometric distortion (below 2%) must be accomplished by implementing static trapezoidal correction in the image generator since the GE Projectors are intolerant of electronic modification of their raster shape.

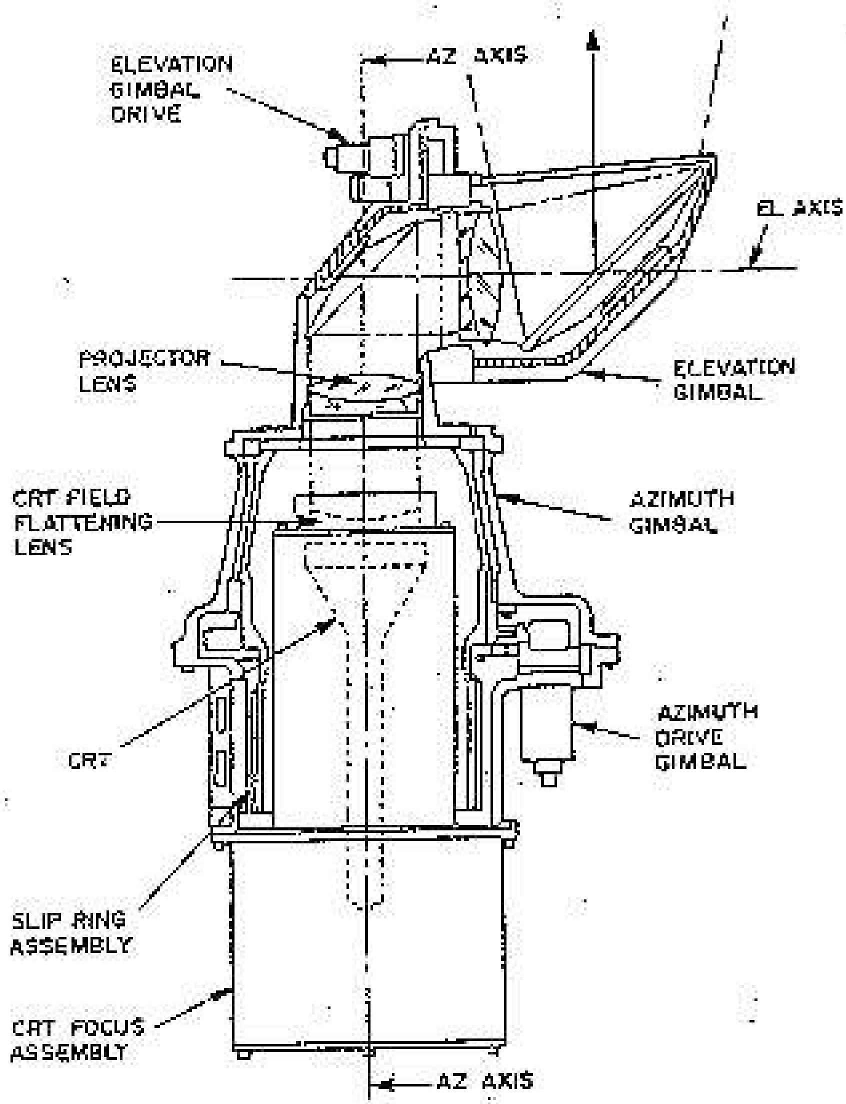


FIGURE 6.15 DIAGRAM OF TARGET PROJECTORS USED ON DEVICE 2E7

TARGET DISPLAY PERFORMANCE

PARAMETER		PERFORMANCE
FIELD-OF-REGARD (EACH PAIR)		360° Horizontal + 90° / –50° Vertical
FIELD-OF-VIEW (EACH PROJECTOR)		23°
SCAN FORMAT		525 line, 2:1 interlace 30Hz frame, 60Hz filed
LUMINANCE		2.4 ft.L. for 3/4-in. target 0.6 ft.L. for 64-in. target
RESOLUTION		1 arcmin/LP for 3/4-in. target 8 arcmin/LP for 64-in. target
COLOR		Monochrome
GREY SCALE		> 6 shades
DISTORTION		Corrected for screen curvature and eye/projector offset. 1:1 aspectg raster to within ±2.5%
SIZE DYNAMIC RANGE		250:1
STATIC POINTING ACCURACY		±0.15% of servo excursion
MAXIMUM SLEWIN6 VELOCITY	AZ Servo EL Servo	10 rad/sec 10 rad/sec
MAXIMUM ACCELERATION	AZ. Servo EL. Servo	20 rad/sec2 40 rad/sec2
SWITCHOVER ERROR BETWEEN PROJECTOR PAIR		< 1°

FIGURE 6.16 TARGET DISPLAY PERFORMANCE

SKY/EARTH DISPLAY PERFORMANCE

PARAMETER	PERFORMANCE
FIELD-OF-VIEW	360° Horizontal +90° to –50° Vertical
LUMINANCE	0.1 ft.L.
RESOLUTION	36 arcmin/LP
COLOR	RGB
SCAN FORMAT	1023 line, 2:1 interlace 30Hz frame, 60Hz field
DISPLAY APERTURE	Non-discernible
MAPPING ERROR	< 1% of display height
PROJECTION FIELD EDGE ALIGNMENT	< 1° Mismatch

FIGURE 6.17 SKY/EARTH BACKGROUND DISPLAY PERFORMANCE

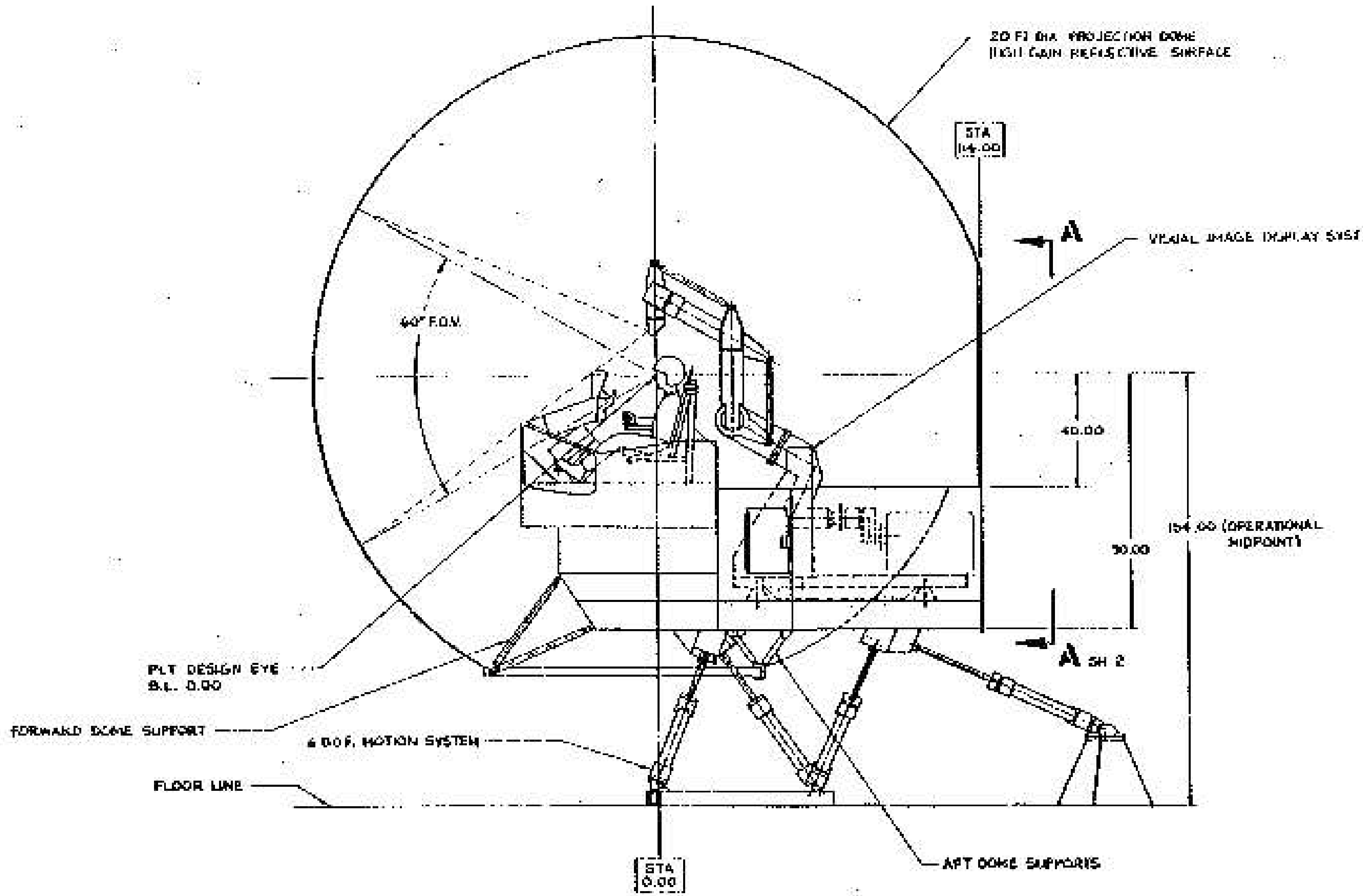


FIGURE 6.10 EBORP

IFOV		60° V x 136°
FIELD OF REGARD	• Azimuath • Elevation • Roll	Continuous through 360° 120° (i.e., –30°/+ 90°) Continuous through 360°
LUMINANCE		15 ft.L.
LUMINANCE VARIATION		Less than 15%
CONTRAST		25:1
RESOLUTION		8 arcmin/OLP
GEOMETRIC DISTORTION		2% (Central 40° circle) 5% (Elsewhere)
IMAGE OVERLAP		1.8° Overlap Registration of ± 3 arcmin

FIGURE 6.19 PERFORMANCE OF ACAVS VISUAL

A requirement of ACAVS is that the FOV be slewable to allow optimization of the visual for different training tasks. However, any FOV change can potentially lead to additional geometric error in the image since the exit pupil/screen/eye point relationship changes. EPORP avoids this pitfall by not only pitching and yawing the exit pupil, but also translating the pupil about the head. This ensures that the angle between the pupil and eye, as measured from the center of the FOV, remains invariant.

7.0 Display Systems Currently Under Development

It is safe to say that a completely satisfactory display system for flight simulation has yet to be found. Virtual image displays like the Beamsplitter/Mirror and Off-Axis systems have problems satisfying FOV training requirements due to packaging difficulties and the cost of so many channels. The PANCAKE Window, though easier to package, requires at least seven channels and, because of its low transmission, requires that a monochrome CRT or light valve be used as an input source. The former alternative precludes full color, and the latter implies medium resolution at best. Real image systems such as LFOV provide only medium resolution and require many channels for a wider FOV. Device 2E7 uses only four channels (though one is specially modified to do double-duty) and employs target projectors to generate high resolution where needed; however, brightness suffers as manifested by a background luminance of only 0.1 ft.L.

Much R&D is currently underway at both commercial and military facilities to resolve these sorts of problems. For better or for worse, solutions appear to be focusing on Area Of Interest (AOI) displays in which some degree of head-tracking (HT) or eye-tracking (ET) is used to concentrate display capability at the point of fixation of a single pilot. The principle in operation here is that as the pilot changes his point of fixation as a result of head or eye movement, this change is sensed by the tracking devices and communicated to both the IG and the servo-controlled display system. The IG computes the image corresponding to what the pilot should be seeing, and the servos slew the display device to an orientation that provides illumination where needed. If the display system is affixed to the pilot's helmet, then the servo-mechanisms may not be required except to compensate for artifacts generated by slowing the head. All in all, the net result is not only that a small number of display channels are required, but that the finite IG capacity can be concentrated where it will do the most good. And, unlike a system using target projection, this concentration of detail is controlled by the pilot rather than being tied to a specified object!

Several limitations currently exist with using HT and ET on display systems. The most obvious is that training two crew members at the same time is either impossible, or at best requires a second complete display system (and possibly a second IG!). Another problem with some approaches is slowing bulky display systems at rates commensurate with head or eye movement. For example, it is not unusual for eye velocities to exceed 700 °/sec and have accelerations of up to 50,000 $°/sec^2$. A comparable problem exists with the image generation system. Even assuming instantaneous update of head or eye position, the IG requires about 100 msec to compute a new image.

It is felt by some researchers that delays inherent with current display and IG technology may not be too damaging to HT and ET because of a physiological phenomenon termed "saccadic suppression". When the eye is moving deliberately to scan or track an object, it moves rapidly in a series of roughly 15° steps termed saccades. During these high-speed movements, imagery moves so quickly across the retina that it cannot be assimililated. Rather than go into sensory overload, the brain appears to suppress visual sensitivity beginning about 100 msec before the saccade commences until about 150 msec after it concludes. Thus, by detecting the onset of a saccade, some fraction of 150 msec exists in which to generate a new image with the IG, and also to reposition the display device for presenting the new image. With this fact lending encouragement to proceed, the next section will discuss HT and ET more specifically.

7.1 Head- And Eye-Tracking

By way of background, Head-Tracking is a means of determining the absolute position and orientation of the pilot's head. It is generally accomplished in one of two ways. A magnetic scheme involves placing a magnetic sensor on the pilot's helmet and attaching a source to the cockpit. Movement of the head generates a differential signal that can be directly related to changes in head position and orientation. **Figure 7.1** illustrates this principle for a magnetic HT produced by PNSI. The second scheme is an optical one and involves placing four LED's on the helmet. Two photo-sensors placed in the cockpit can triangulate on these LED's and derive head position and orientation. Nominal values for angular and positional accuracy of a magnetic HT is roughly 6 arc-minutes and 100 mils, respectively.

Eye-tracking is a refinement on HT in that it capitalizes on the roll-off in visual acuity as an object approaches the periphery of the visual field. Several schemes for detecting the line-of-gaze vector exist; the one discussed here is made by Applied Sciences Laboratory and is based on measuring the separation between the centroids of the pupil and corneal reflections of the eye using helmet-mounted instrumentation. Both centroids are required since measuring only one or the other would not permit differentiation between eye rotation (normal and expected) and eye translation (not expected, but possible if the pilot's helmet does not fit tightly). **Figure 7.2** illustrates the structure of the eye and the location of the line-of-gaze vector (cf. visual axis). **Figure 7.3** shows some representative centroids of reflection. The ASL ET obtains its information by interrogating one of the pilot's eyes with infrared (IR) light. The reflected light is detected by a miniature CCD camera, after which signal processing is used to determine the two centroids and, subsequently, the line-of-gaze vector. The horizontal and vertical coordinates of this vector is updated at 60 Hz and has an accuracy of better than 1.25° within a 30° radius visual field.

Having discussed these two important tools of the display engineer, the following sections will address some of the systems into which they are being incorporated. Some leave the head unencumbered, having projectors that are slaved to head and eye motion, and require powerful servo-mechanisms to slew one or more projectors about. Another uses a dome as a viewing screen, but attaches the projector to the pilot's helmet. Still another puts the displayed imagery on the helmet, but locates the display input device remotely. One has both the display input device and viewing system integrated with the pilot's helmet, and this will be discussed initially.

7.2 VCASS

VCASS (Visually-Coupled Airborne Systems Simulator) is an Air Force program that seeks to use a relatively low-cost helmet-mounted virtual imaging system rather than a dome/projection system or mosaic of PANCAKE Windows in order to generate high-quality, wide FOV visual scenes for simulator training. VCASS uses a helmet made by Farrand Optical which incorporates a binocular viewer. Each part of the viewer is comprised on a one-inch monochrome CRT which is collimated by a miniature PANCAKE Window. The output of the PANCAKE is viewed via a beamsplitter to permit viewing of the aircraft controls. A Polyhemus magnetic HT is incorporated into the system to permit the trainee to freely look about. **Figure 7.4** roughly illustrates the appearance of the anticipated VCASS system.

Owing to a 14mm diameter CRT developed by Thomas which produces 1600 ft.L. with a 16 micron spot, brightness at the eye is about 10 ft.L. and resolution is about 875 lines. Each eyepiece has a 60° vertical x 80° horizontal FOV. Total instantaneous FOV is adjustable, but is nominally 60° x 120° to provide for a 40° overlap region in the center of the visual field. If a dual eyepoint IG is used to generate a scene for each eye location, then stereopsis is present in the overlap region. A binocular display such as this may enable more precise judgements of distance between two aircraft when training critical tasks such as aerial refueling.

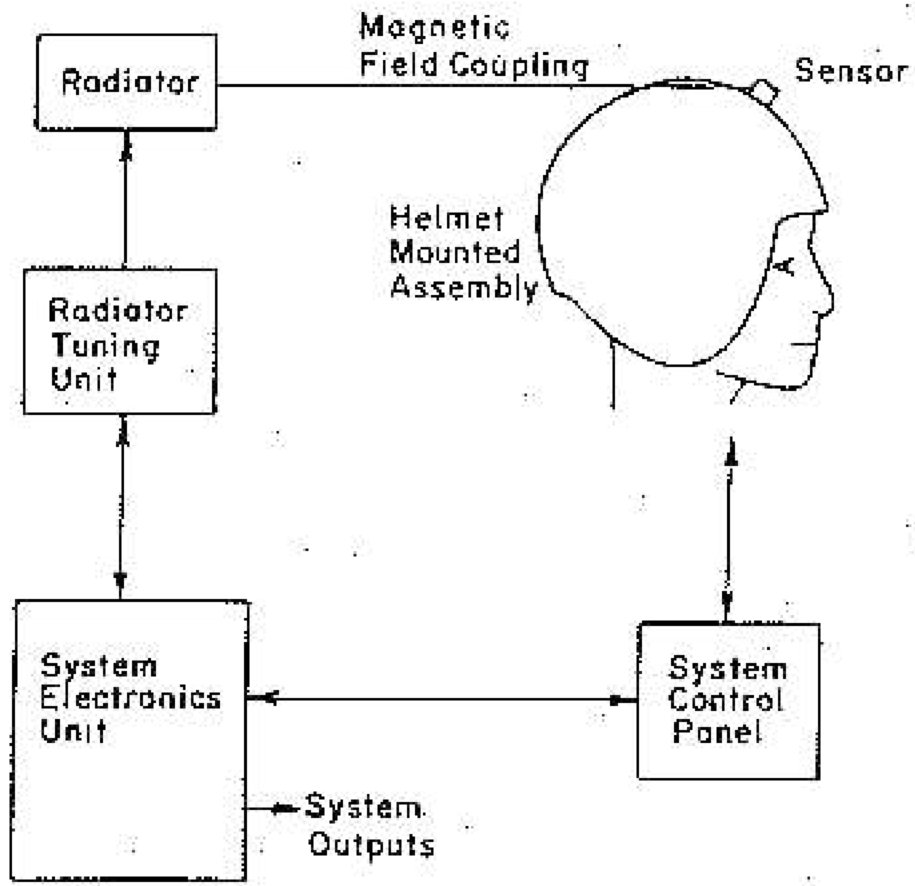


FIGURE 7.1 MAGNETIC HEAD-TRACKING

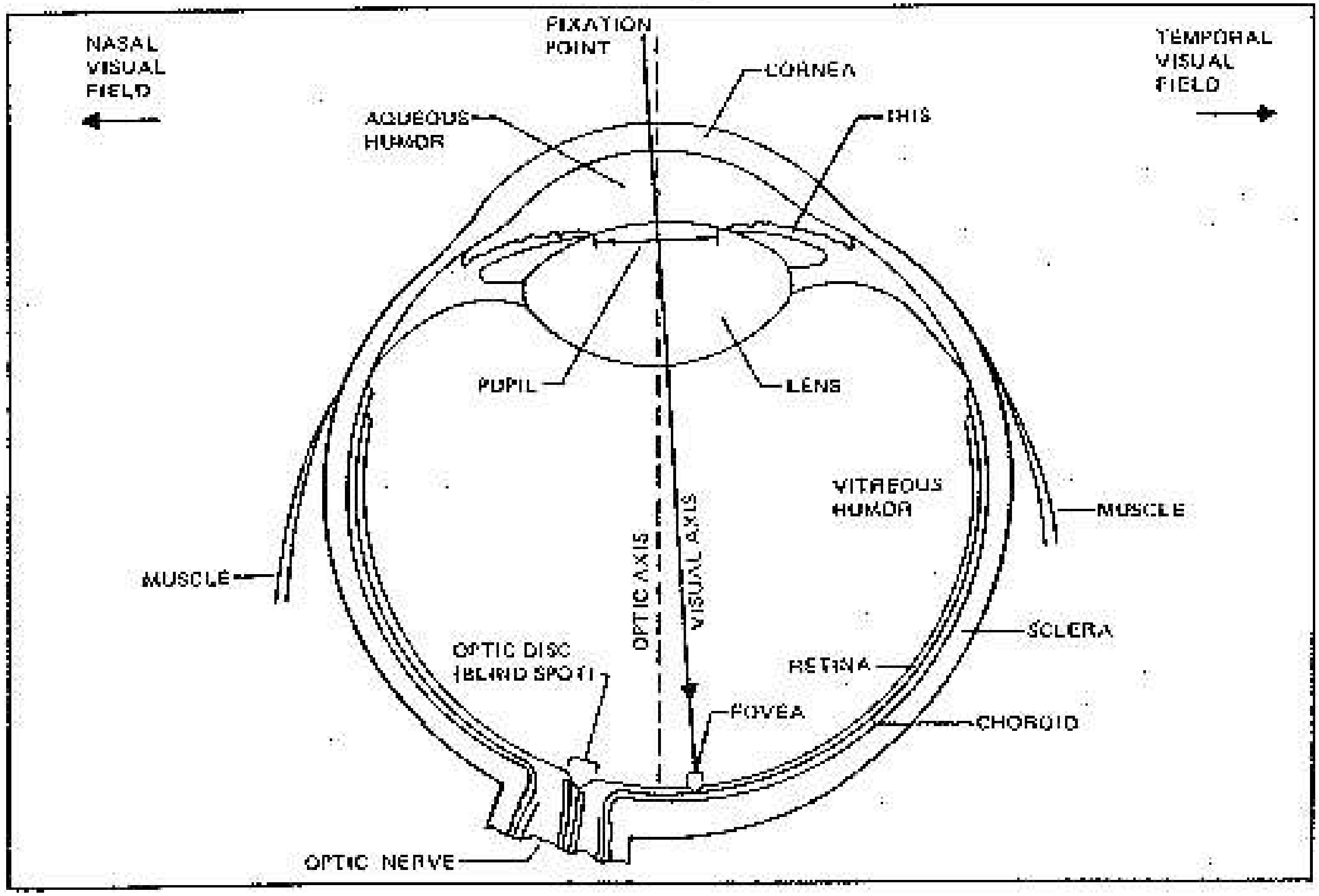
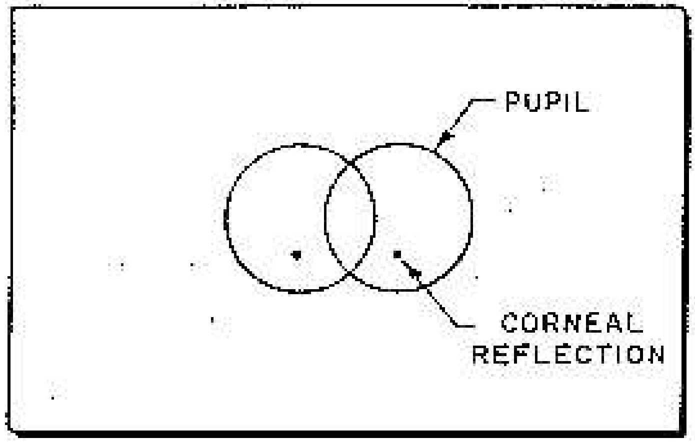
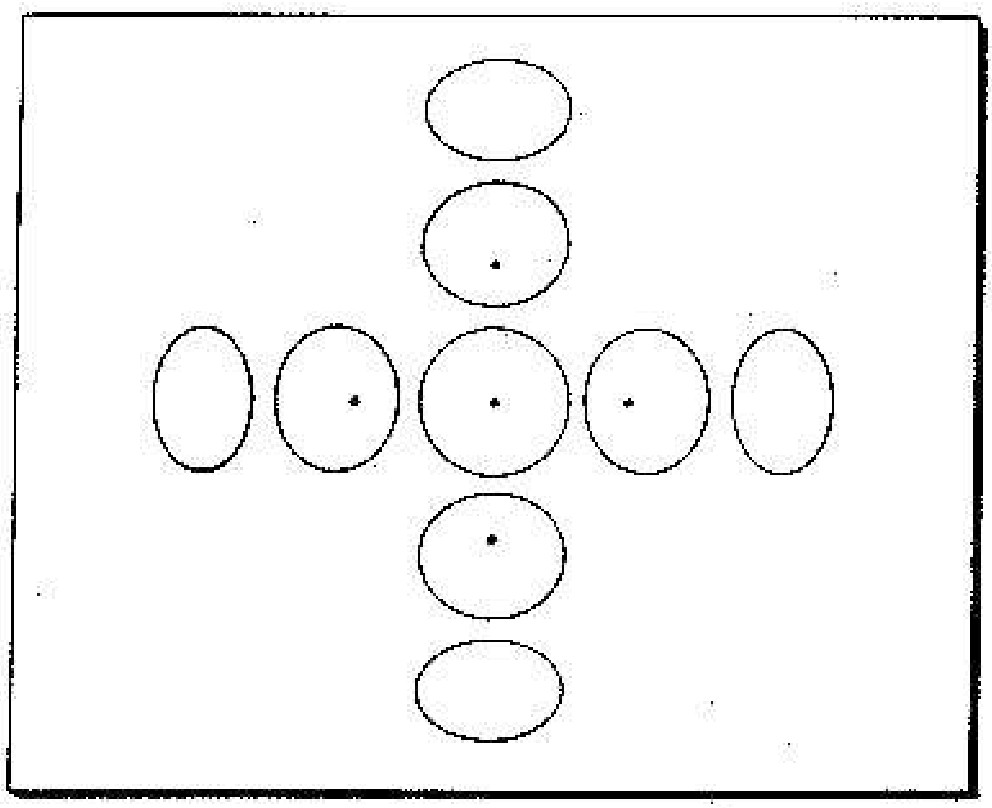


FIGURE 7.2 DEFINITION OF VISUAL AXIS (LINE OF GAZE)



(a) Translation of the Eye



(b) Rotation of the eye (exaggerated)

FIGURE 7.3 TRANSLATION VS. ROTATION OF THE EYE

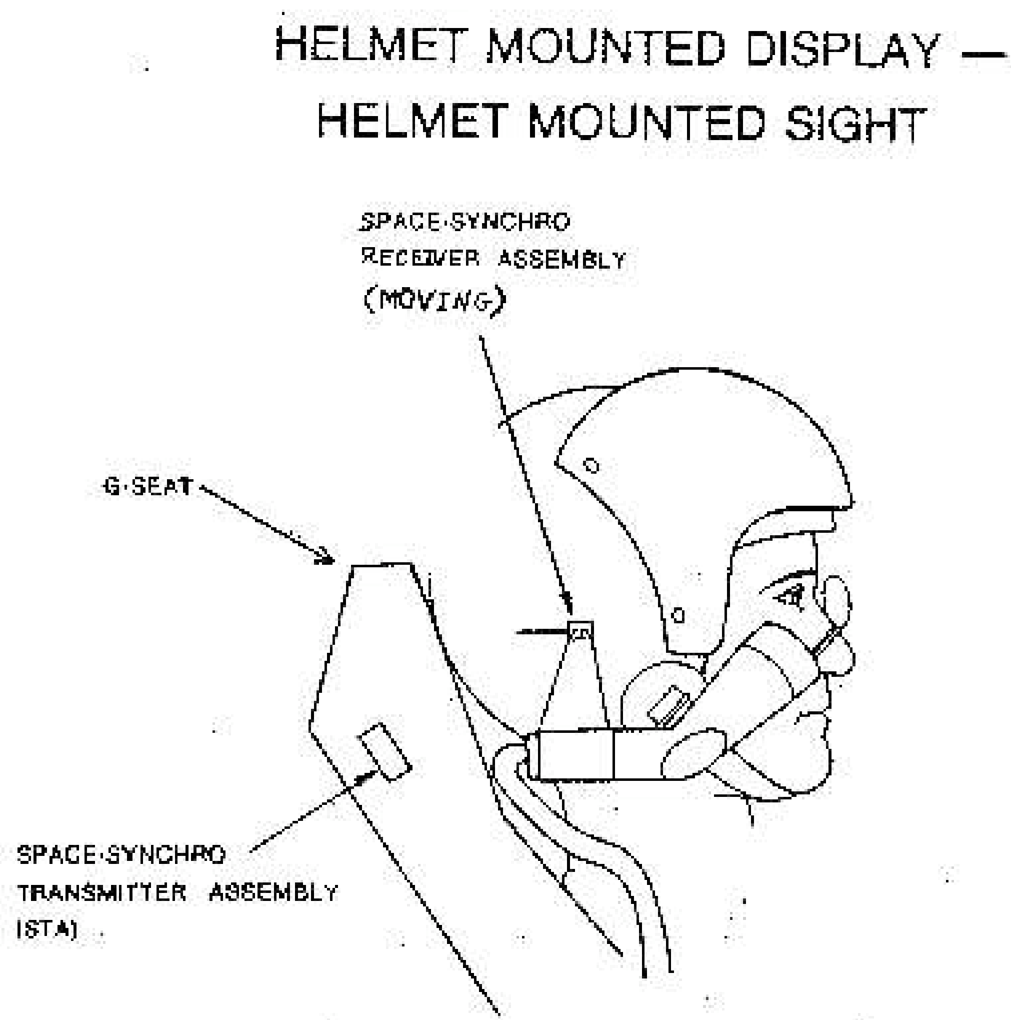


FIGURE 7.4 HELMET CONCEPT FOR VCASS

Three problems characterize the VCASS display. The first is that the helmet is fairly encumbered with hardware, making it more uncomfortable to wear than it would be otherwise. Second, no provision has yet been made to occult the imagery when the pilot gazes down at his controls. And third, rapid slewing of the head can result in "rubber banding". This artifact arises when the head significantly translates while an object is being drawn by the display device. Perceptually, it appears that the bottom of the object is stretching in the direction of head motion. In principle, however, this can be compensated for electronically.

7.3 FOHMD

The FOHMD (Fiber Optic Helmet-Mounted Display) is a program being developed by CAE (Canada) for the Air Force. Initially, the program involves a helmet with HT that presents a virtual image to the pilot via a binocular viewer, much like VCASS and illustrated in **Figure 7.5**. Each half of the viewer contains a miniature PANCAKE that is viewed via a beamsplitter. However, rather than being driven by onboard monochrome CRTs, the FOHMD derives its imagery from four 750 lumen, color GE Light Valve Projectors located behind the pilot and optically coupled to the helmet using four fiber optic cables acting as coherent light pipes. **Figure 7.6** illustrates the breadboard setup located at AFHRL.

Each eye receives information from two cables, as shown by **Figure 7.7**. One cable provides a 60° vertical x 80° horizontal FOV having 5.0 arcmin per pixel resolution. The other cable provides a centered high-resolution inset of either 25° x 25° with 2 arcmin resolution or 37° x 37° with 3 arcmin resolution. The total instantaneous displayed FOV is 135° x 60°, thus resulting in an overlap region about 25° wide in which steropsis can be generated. Brightness of the full-color imagery is expected to be about 80 ft.L. Plans exist to incorporate ET onto the helmet, allowing the high resolution inset to be dynamically positioned with eye movement.

The problems inherent with VCASS are applicable for the FOHMD as well; i.e., helmet bulk, need to occult imagery when looking at the controls, and rubber banding. An additional problem is that transmission though the discrete fiber bundles gives the image an appearance of being viewed through a screen door. These issues are being addressed, however. Helmet bulk will be reduced by reducing fiber cable size while combining the background and inset cables into one. Rubberbanding is being eliminated by using head acceleration information to predict image position and compensating by physically translating the fiber bundle ends relative to the light valve projector in real time. Several approaches are being considered to eliminate the screen door effect, all of which involve mechanisms for spreading image information over more than one fiber and putting the image back together again before displaying it.

7.4 Helmet-Mounted Laser Projector

This particular display device is part of the Visual Display Research Tool (VDRT) developed by American Airlines and Rediffusion Simulation, Ltd. for implementation on the Visual Training Research Simulator (VTRS) at the Naval Training Equipment Center. The concept is illustrated in **Figure 7.8**. An image generator is used to modulate the intensity of red, green, and blue laser light. This light is coupled via fiber optic cables to the helmet of the pilot, after which it is projected onto a retroreflective (i.e., extremely high gain) screen material applied to the inner surface of a dome. The image is composed of a wide-angle, low resolution background termed the Instantaneous Field Of View (IFOV) and a high resolution, inset Area of Interest (AOI). Head-tracking and helmet-mounted eye-tracking are employed to provide line-of sight information to the IG, thus ensuring that picture information will correspond to the pilot's gaze direction.

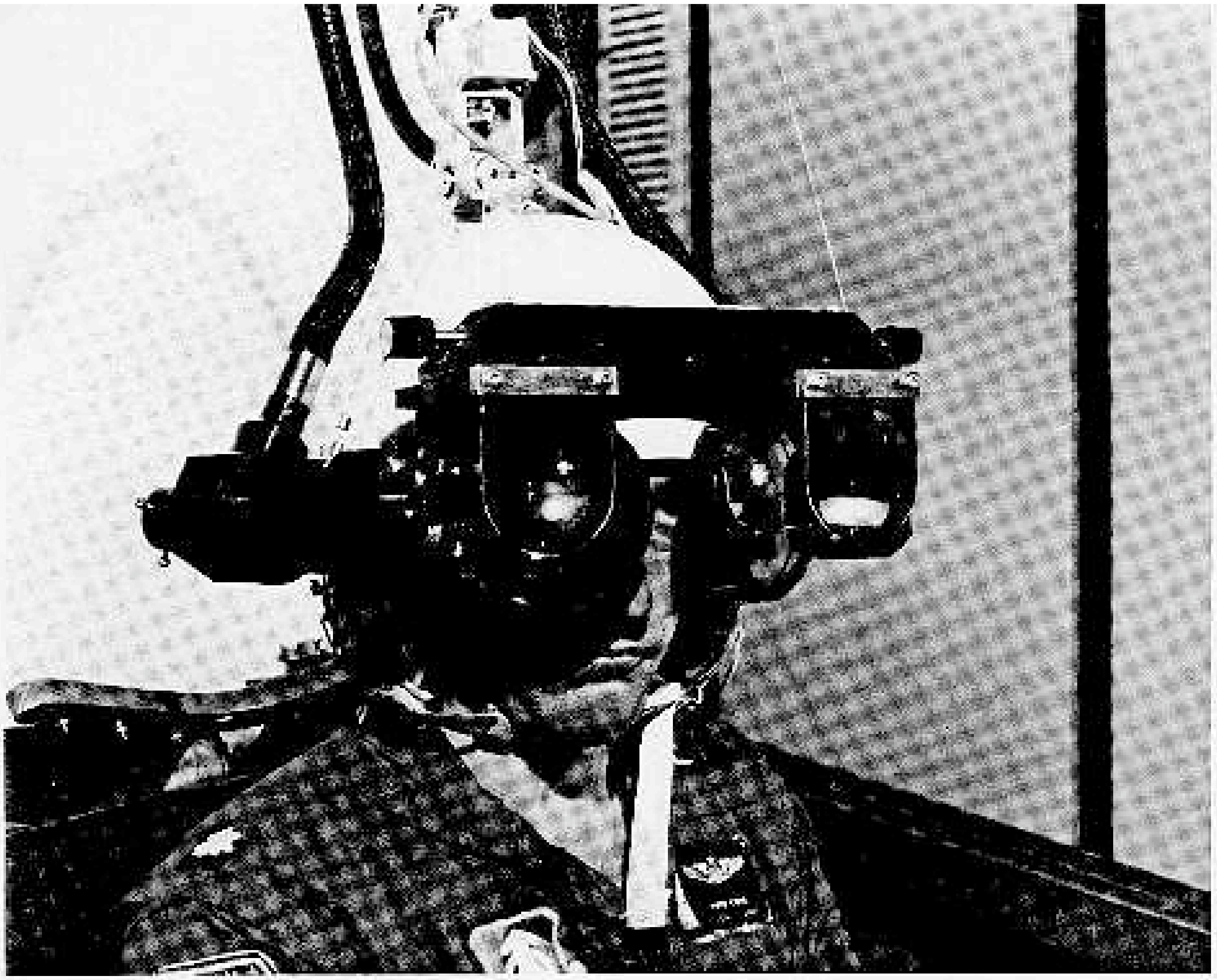


FIGURE 7.5 PICTURE OF FOHMD

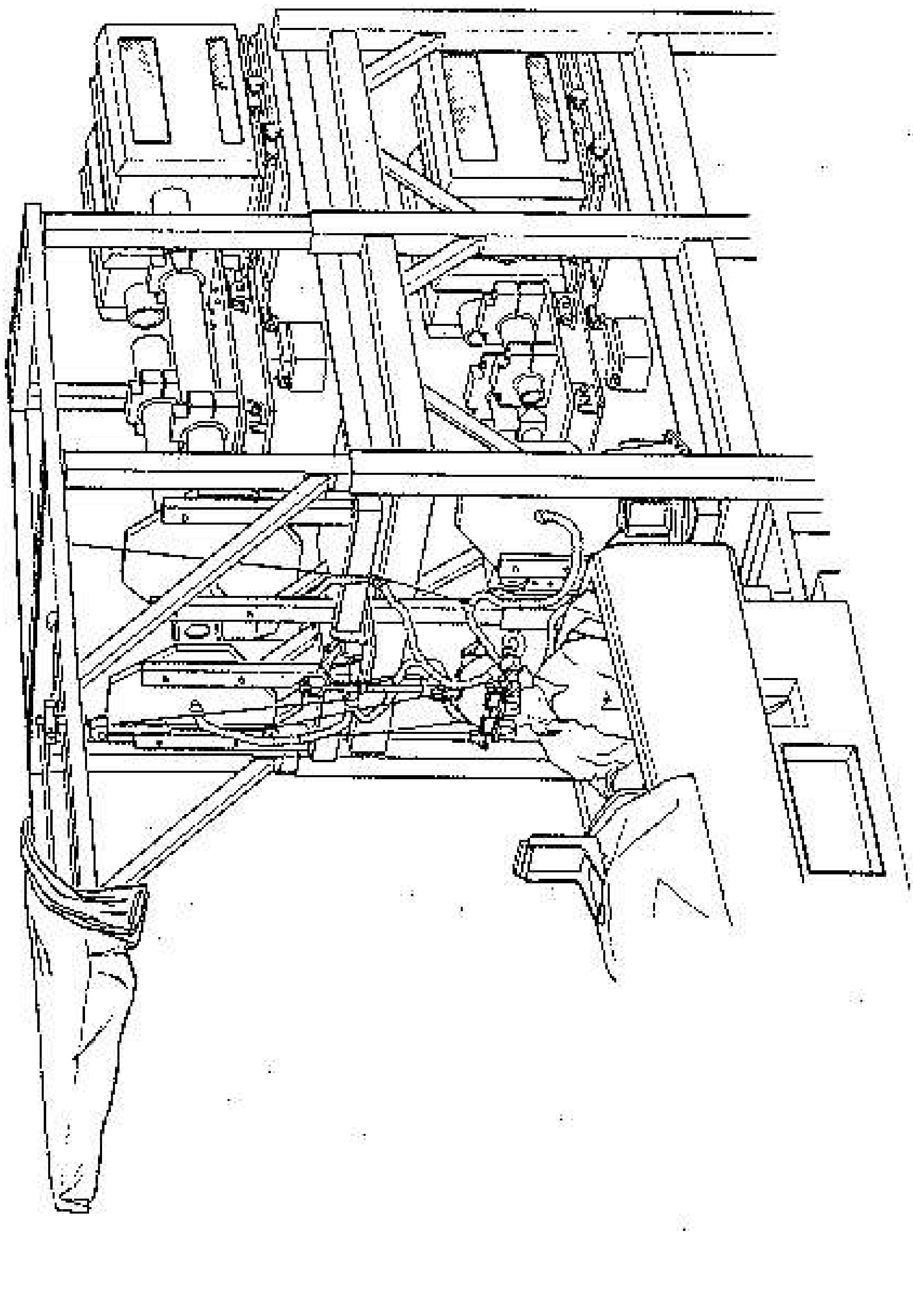


FIGURE 7.6 BREADBOARD SETUP OF FOHMD

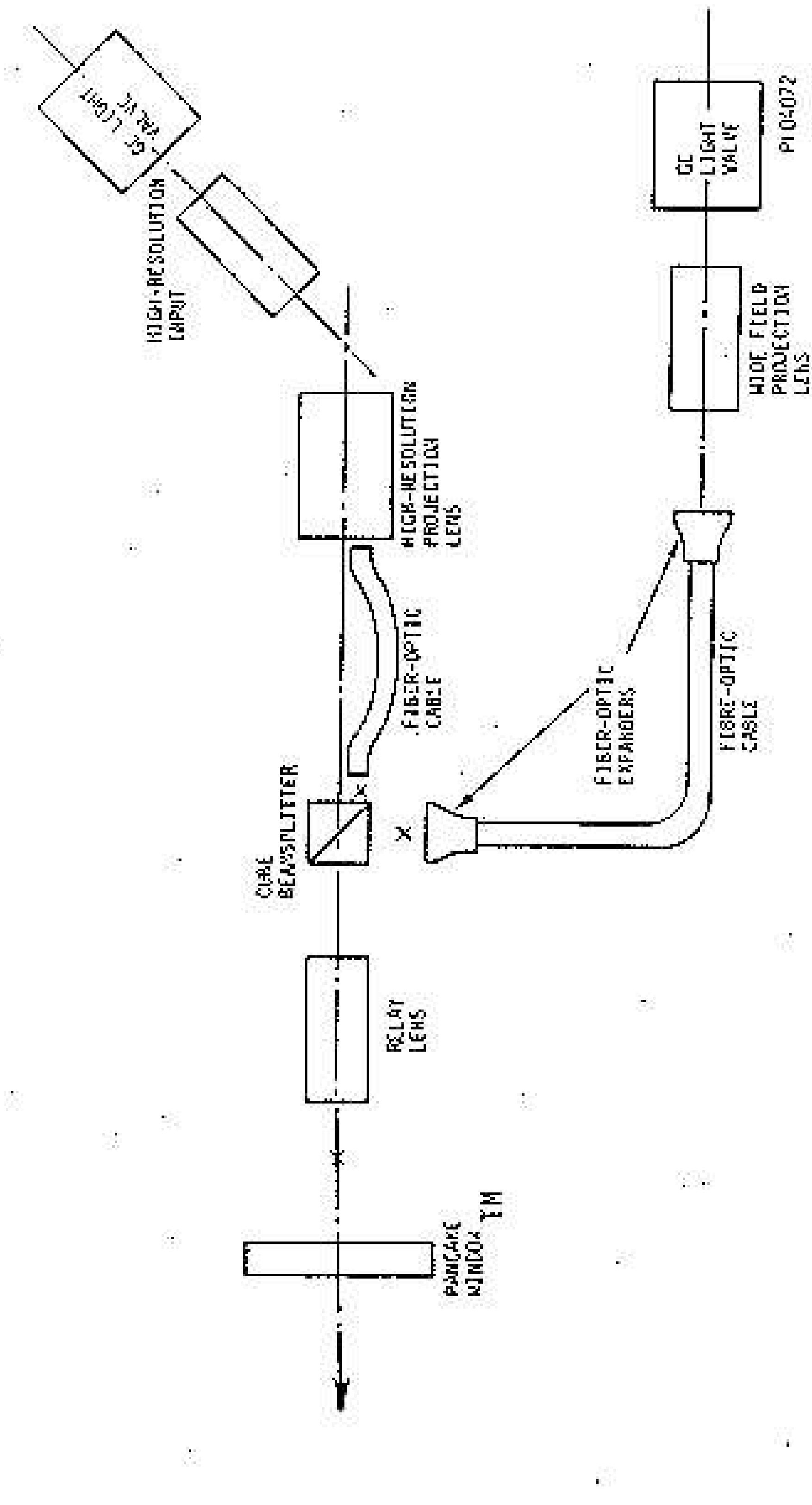


FIGURE 7.7 COUPLING OPTICS IN FOHMD BETWEEN PROJECTORS AND FIBER CABLES

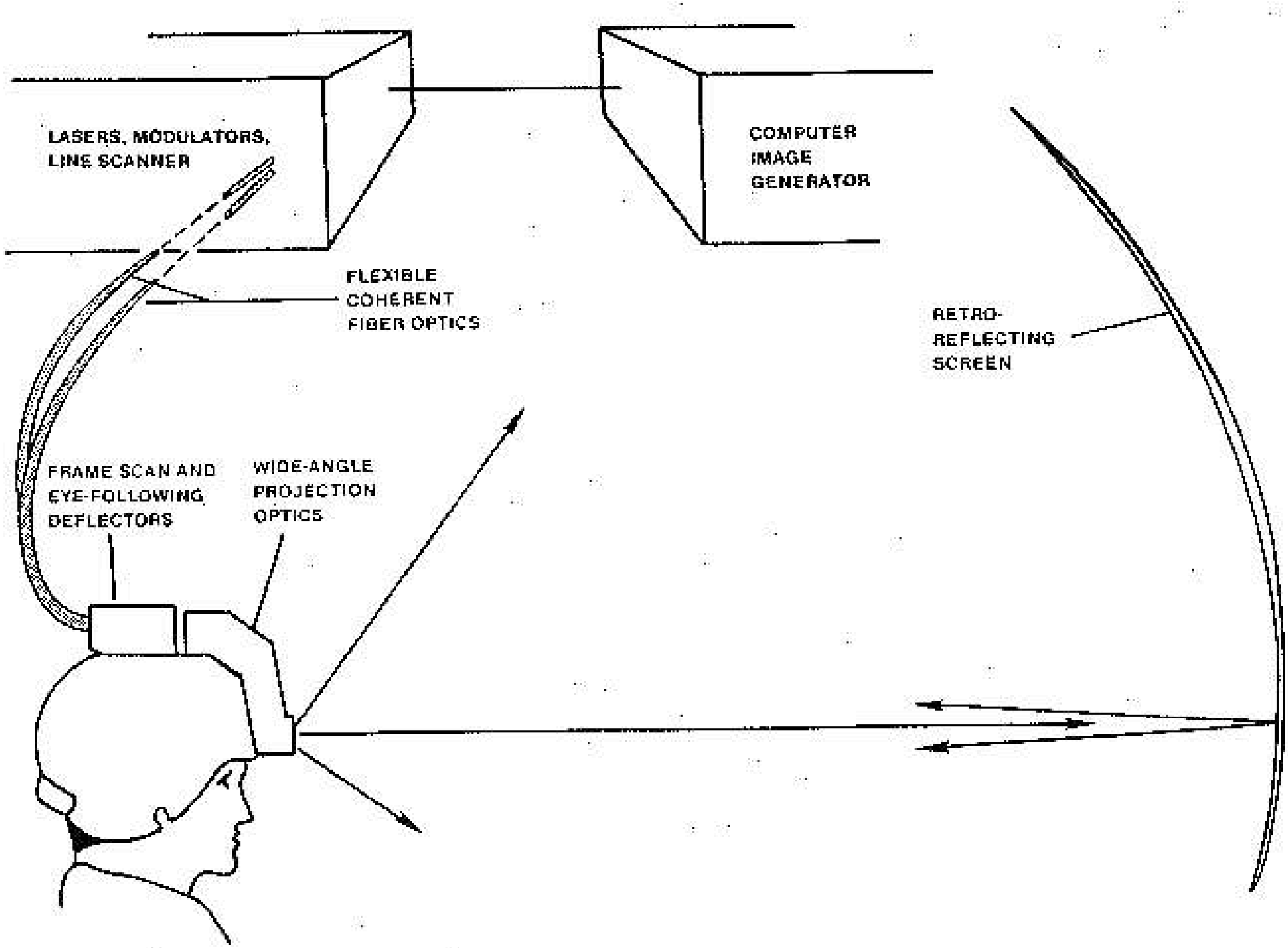


FIGURE 7.0 CONCEPT OF HELMET-MOUNTED LASER PROJECTOR

Turning this concept into reality begins with the off-helmet portion of the display system illustrated in **Figure 7.9**. Argon and dye lasers generate two each red, green, and blue laser beams that are modulated by the IG output. Three of the beams correspond to the IFOV and three to the AOI. Each of the trios is recombined, resulting in full color IFOV and AOI laser beams that are slightly separated. These beams are simultaneously scanned to form linear images corre-sponding to single raster lines which ate then coupled into flexible coherent fiber optic ribbon cable. At the output end of the fiber cables is the pilot's helmet, as shown in **Figure 7.10**. On the helmet is a capability to provide controlled offsets of the line images so as to compensate for rapid head motion (re: rubber banding). The raster lines comprising the IFOV and AOI are transformed into 2-D images using two galvonometer-driven mirror scanners. The two beams are combined and then relayed to a point about two inches from the pilot's eyes for wide angle projection onto the 10 foot radius retro-reflecting dome surface. This surface is targeted to have a gain between 100 and 1,000 since light incident on the dome need only be efficiently reflected over a 1.5° cone if the pilot's head is located at the center of the dome.

It is expected that the additional weight contributed to the pilot's helmet by the optical apparatus will only be 2.5 pounds. Concerning performance, FOV will only be limited by cockpit structure and the extent of the useful dome surface. The IFOV will be 145° diagonal with an inset AOI of 36° diagonal. IFOV resolution is 13 arcmin per line pair; AOI resolution is 3.3 arcmin per line pair. Displayed imagery will be full color and have at least 10 ft.L. brightness and 30:1 contrast.

Using a helmet-mounted projector in conjunction with a retro-reflective screen has several advantages over VCASS and FOHMD types of displays. First of all, it does not impede the pilot's normal view of the cockpit with beamsplitters, and does not limit his instantaneous field of view with restrictive helmet-mounted optics. Secondly, automatic blanking of the outside scene occurs when the pilot looks down at his controls and instruments because these surfaces are not retro-reflective. And finally, two or more people can train simultaneously in the same cockpit, assuming each has a helmet-mounted projector, because the retro-reflective screen suppresses cross-talk; i.e., each crewman can only see his particular IFOV and AOI imagery.

Aside from the previously discussed problems associated with head-tracking, eye-tracking, and transmitting imagery through fibers, only two additional problem areas suggest themselves. One is the question of laser speckle, a phenomenon that effectively degrades resolution. It arises because coherent light, when reflected from a surface, acts as an array of point source emitters which interfere with each other. The eyes of an observer tend to average this interference over resolution elements, thus creating a fine speckle that changes with even the slightest head or screen movement. The other problem area is also laser-related and concerns the cost and reliability of the lasers themselves. The plasma tube of an Argon laser is expensive and difficult to change out. The dye of a dye laser is potentially messy and requires periodic replacement to ensure optimum performance.

7.5 ESPRIT

ESPRIT (Eye-Slaved Projected Raster Inset) is a Singer-Link independent development effort that provides a dome-projection real image system having a high resolution Area Of Interest (AOI) that coincides with the pilot's Line Of Sight (LOS). Unlike the helmet-mounted projector discussed previously, the ESPRIT helmet carries only an eye-tracker and head-tracker; separate background and AOI projectors are remotely located above and behind the cockpit. The background projection remains fixed, whereas the AOI projection can be servo-positioned as a function of the LOS. To inset the AOI, an undersized hole is cut out of the background image and replaced by the AOI inset. An overlap of about 3° results at the border between background and AOI imagery. Using electronic blending at this border then gives the appearance of a continuous image. **Figure 7.11** illustrates the relationship among background, AOI, and blend region.

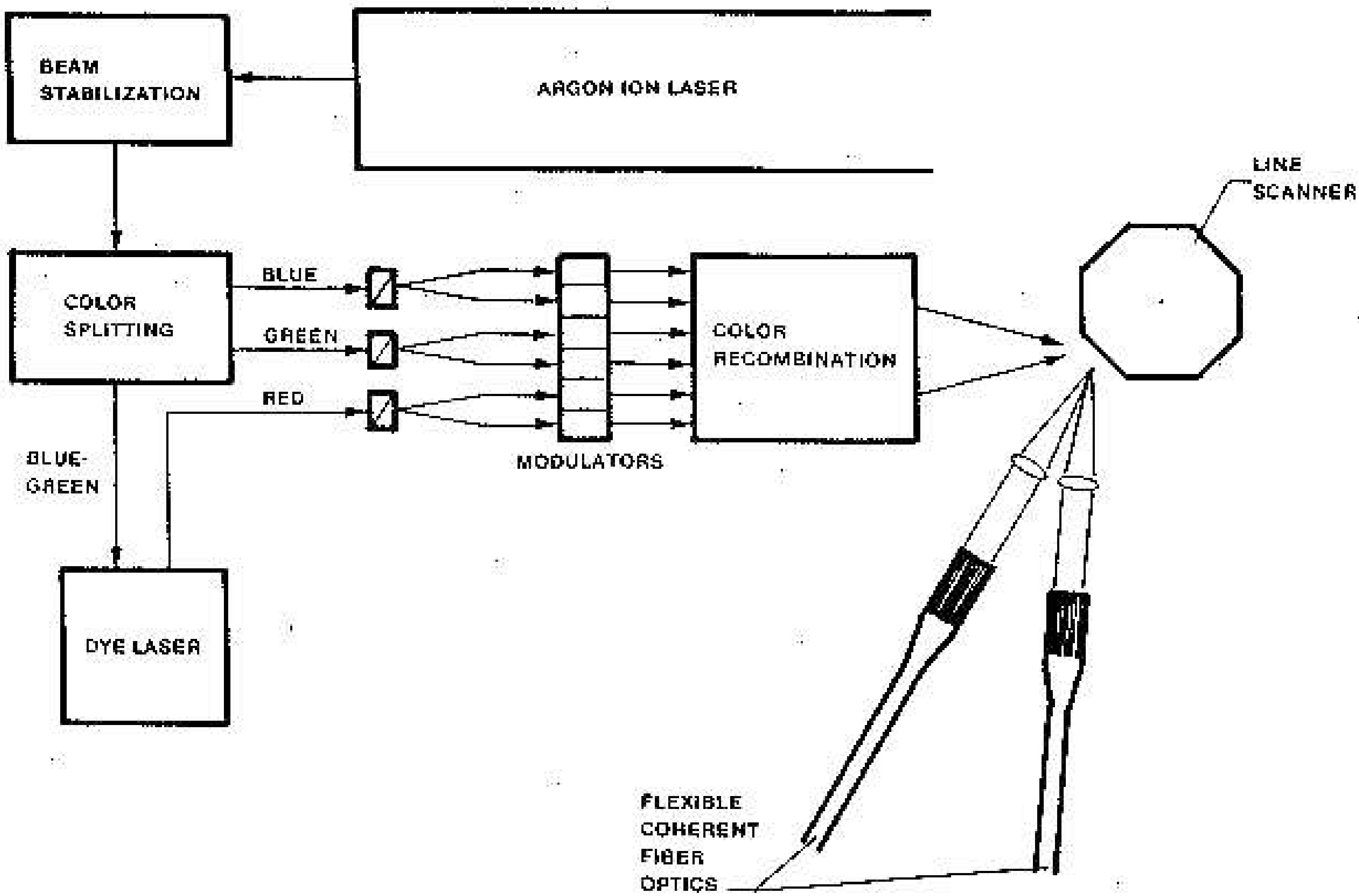


FIGURE 7.9 OFF-HELMET MODULATION AND INSETTING OF AOI FOR VDRT

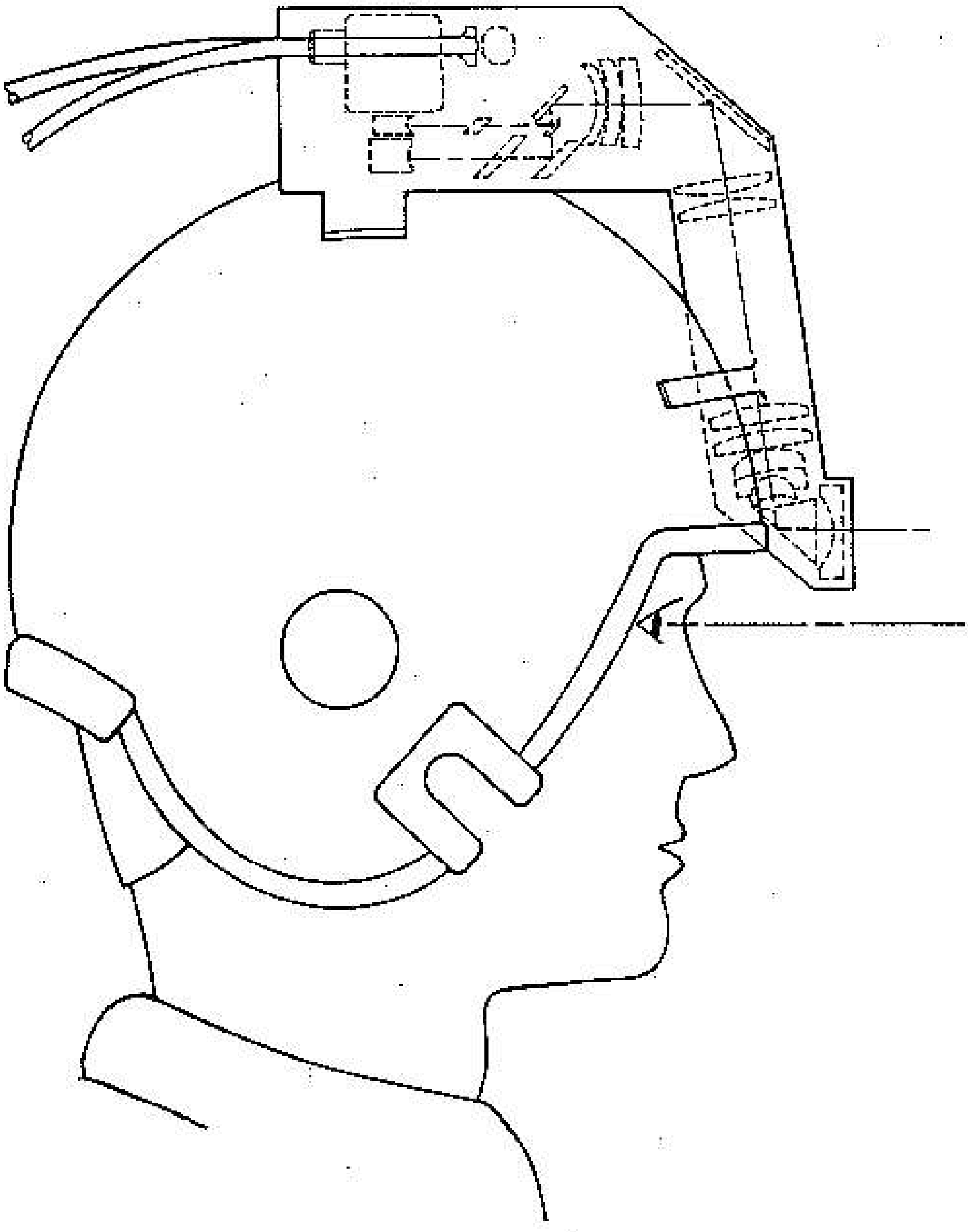


FIGURE 7.10 SCHEMATIC OF HELMET-MOUNTED LASER PROJECTOR

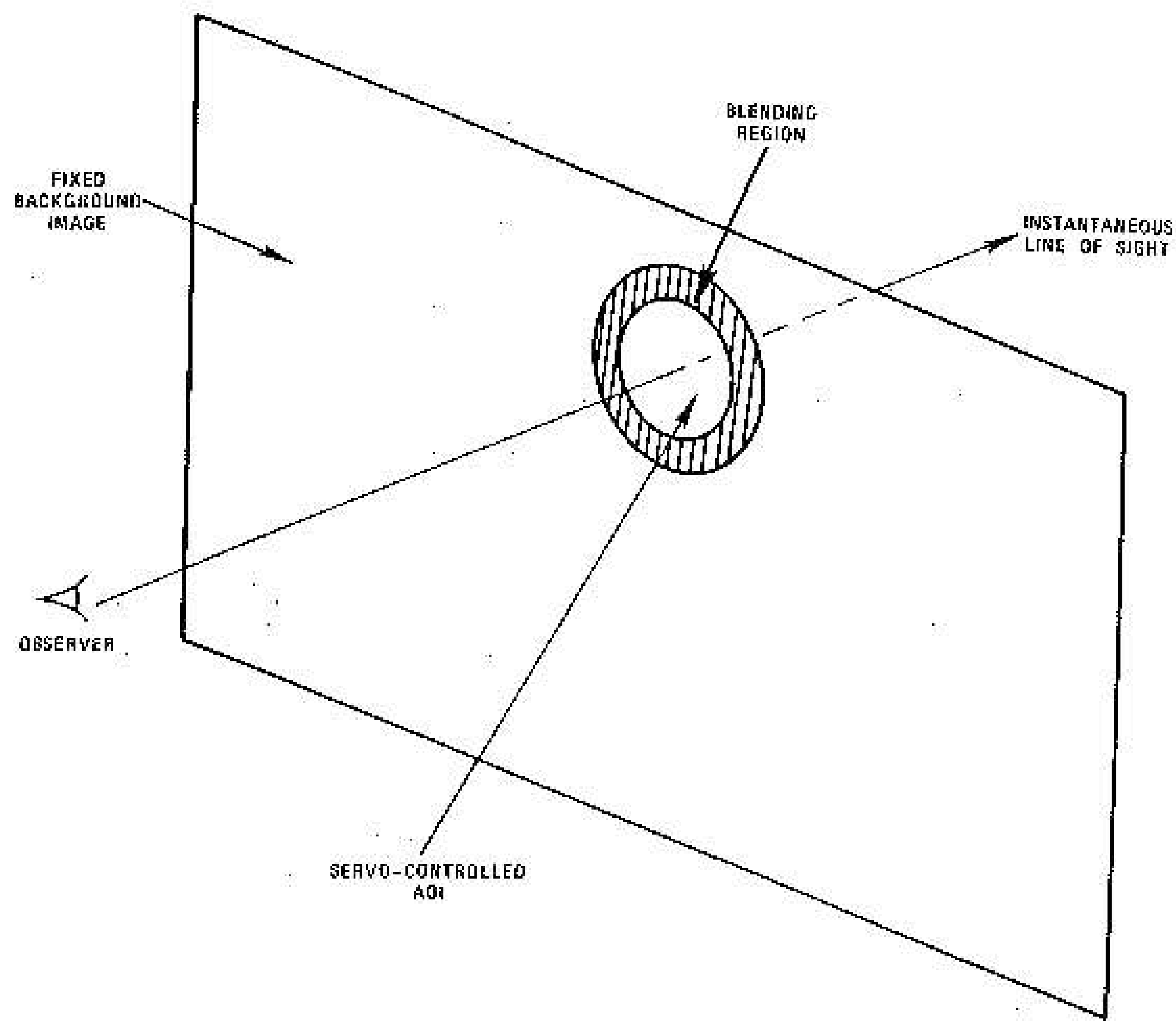


FIGURE 7.11 RELATION BETWEEN BACKGROUND, AOI, AND BLEND REGION WITH ESPRIT

Figure 7.12 contains a block diagram of the ESPRIT system. The background FOV will be filled by three GE Light Valve Projectors, resulting in 270° (± 135°) horizontally by 130° (–50°/+80°) vertically. The AOI will subtend 18°; this includes the 3° overlap region. Imagery will be full color and have a luminance of at least 5 ft.L. Resolution of the background and AOI are 22 arcmin per line pair and 3 arcmin per line pair, respectively.

A breadboard version of ESPRIT is currently being tested with joint Air Force and Navy sponsorship under the auspices of the EDIT (Eye-slaved Display Integration and Test) program. Results are encouraging, but questions still remain concerning (i) effects of IG transport delay, (ii) the perceptual acceptability of the high resolution inset process and (iii) the 18° size of the AOI inset. Given that the concept can be packaged and successfully implemented in a dome, the traditional problem area of training multiple crew members also arises. It should be noted, however, that this scheme does afford a pilot the benefits of visually-coupled AOI with only a modicum of auxiliary hardware attached to the helmet.

7.6 VSCDP

The Visual System Component Development Program (VSCDP) is yet another AOI display and is currently under contract to General Electric for its development and application to the AH-64 Apache Helicopter Simulator. **Figure 7.13** shows an artist's concept of the device's eventual appearance. Conceptually, the device is most like the Helmet-Mounted Laser Projector (described in Section 7.4) since low-resolution background imagery and high-resolution AOI imagery are fixed relative to each other and slowed together. An important difference, however, is that the projection devices of VSCDP are mounted remote from the helmet, thereby potentially enhancing pilot acceptance of the device.

Figure 7.14 is a block diagram of VSCDP. As the pilot moves his Line Of Sight (LOS) and/or head, the Eye/Head Tracker (EHT) measures at a 60 Hz rate the head position and attitude, plus the eye LOS angles relative to the head. The vector sum of the head and eye LOSs is then output to the Display Computer. This computer provides many needed capabilities, including:

1. Deadband functions to filter EHT data so as to ignore noise and involuntary micro-saccades of the pilot.

2. Rate-limiting functions to control the angular step of the image generator (IG) and Servo-Optic Component (SOC) per field time,

3. Computation of view window parameters for input into the IG, and

4. Computation of drive parameters to the SOC gimbals.

The SOC is an opto-mechanical component that was developed by Contraves Goerz (Pittsburgh, PA) to accept imagery from GE Talaria Projectors, optically blend the AOI and background, optically derotate the composite image, and project it onto the dome screen in the proper location. A single GE projector services the AOI image. However, two projectors are used for the background image to ensure sufficient luminance. One supplies the green color component; the other supplies red and blue components.

VSCDP design performance is summarized in **Figure 7.15** for the anticipated case of operating in a 24' diameter dome. Instantaneous FOV is 60° vertically x 140° horizontally. AOI resolution is nearly eye-limiting; luminance is adequate at 4 ft.L. Though not specified, presumably geometric accuracy is ensured for this asymmetric configuration (e.g., eye point is 36 inches below exit pupil) by utilizing dynamic distortion correction available on some Igs.

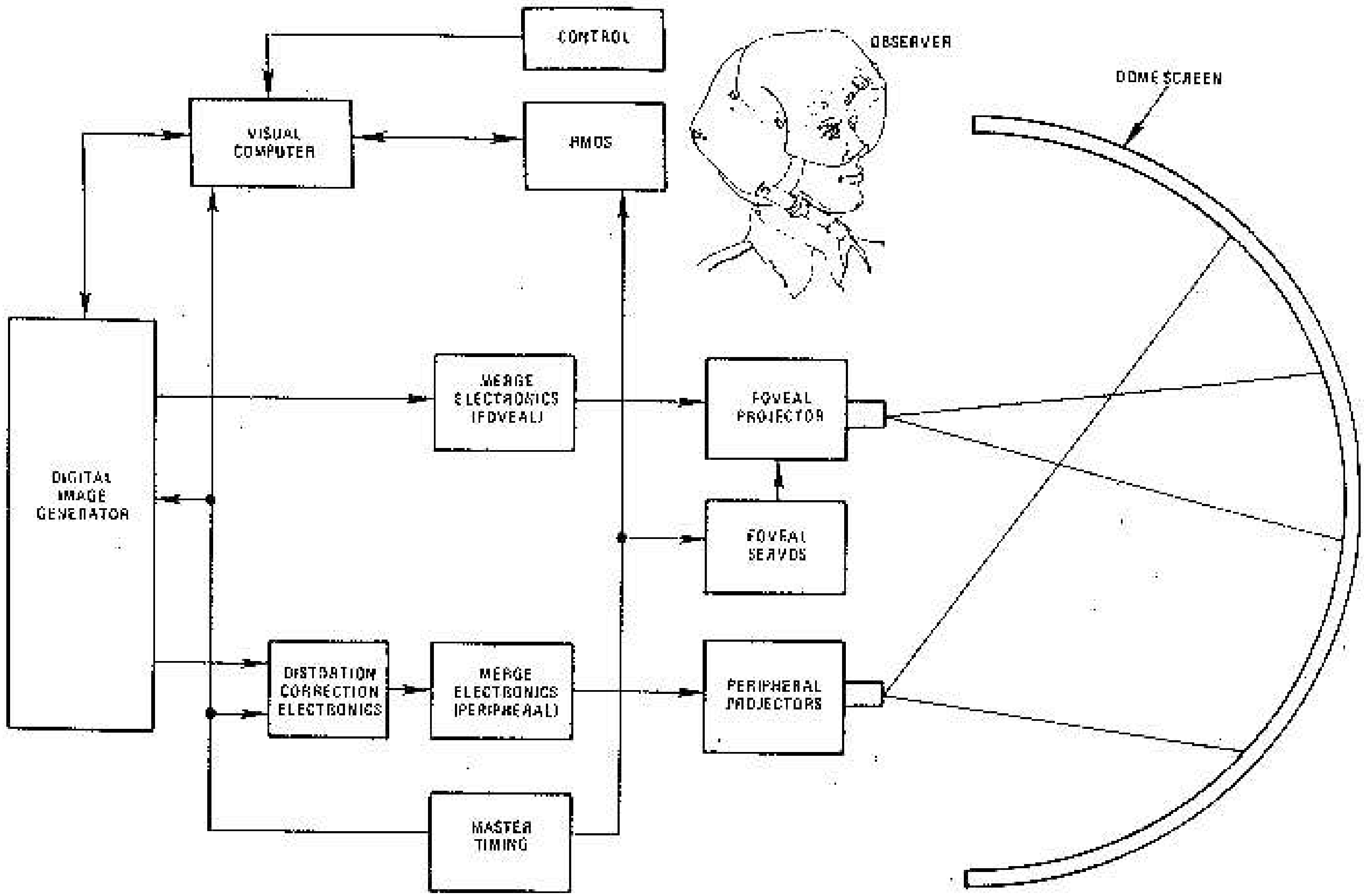


FIGURE 7.12 BLOCK DIAGRAM OF ESPRIT

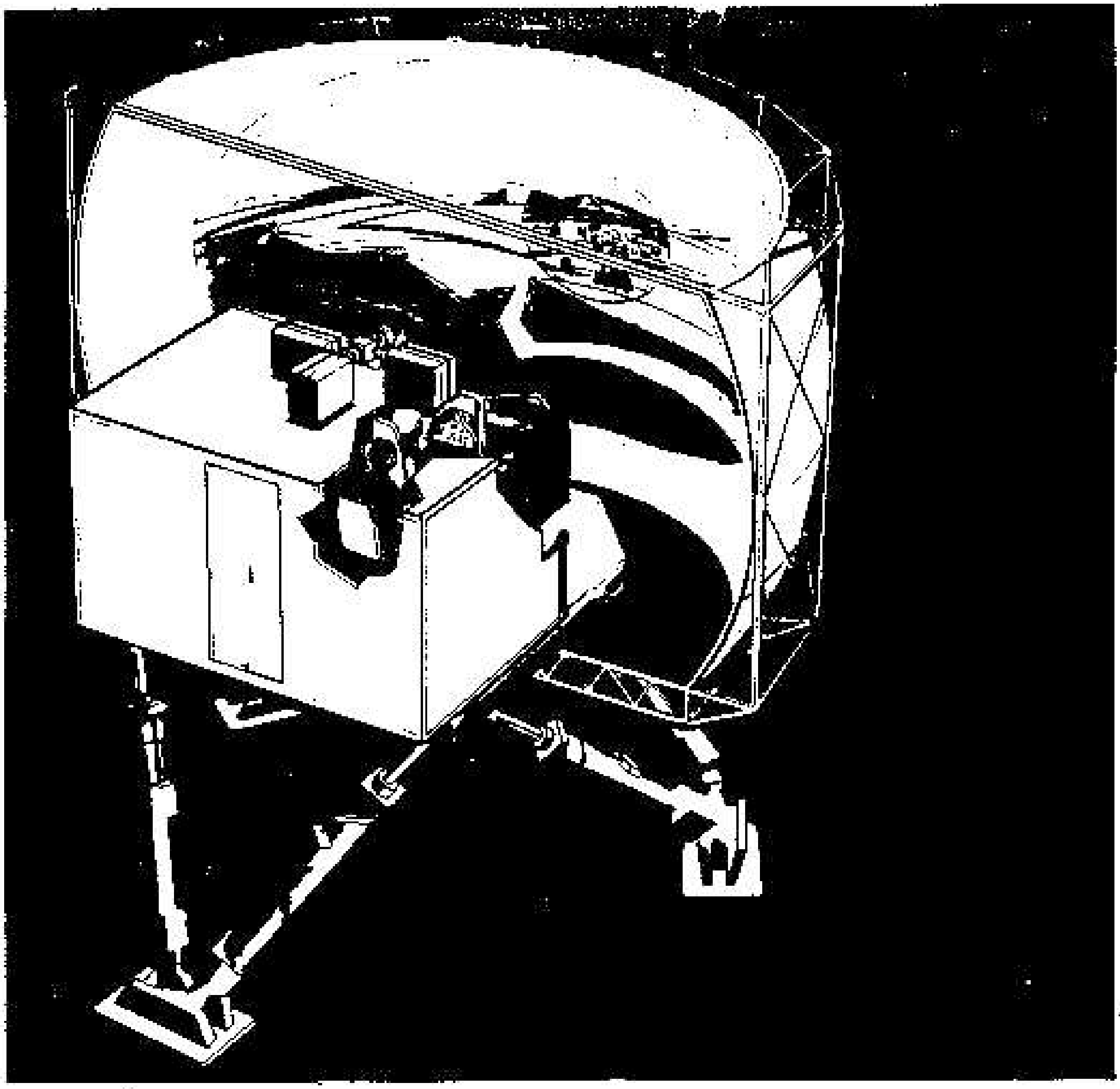


FIGURE 7.13 VSCDP APPEARANCE

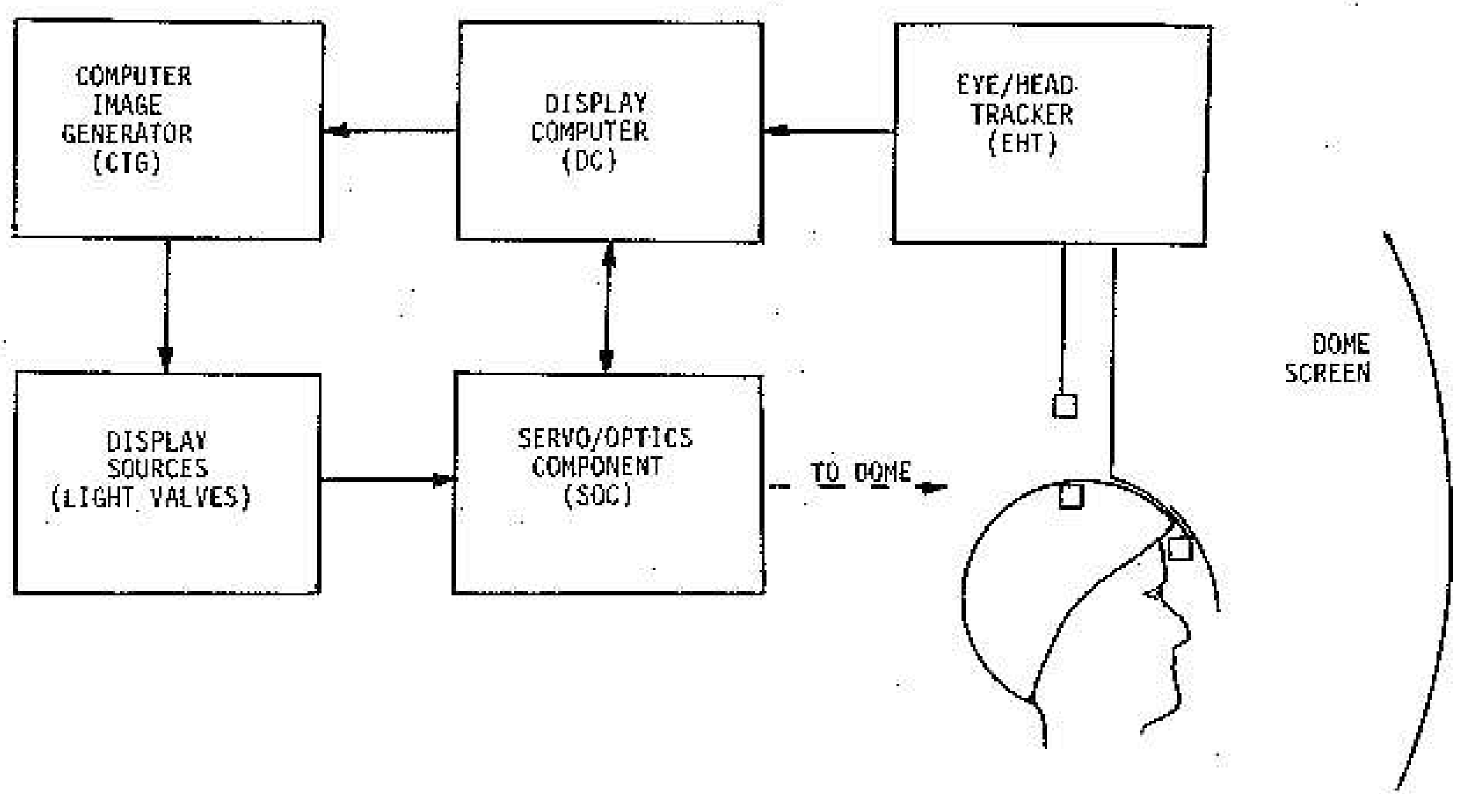


Figure 7.14 BLOCK DIAGRAM OF VSCDP

FIELD OF VIEW	
• Background	60° V x 140° H
• AOI	20° V x 26° H
FIELD OF REGARD	
• Azimuth	± 90°
• Elevation	+30° / –40°
LUMINANCE	4 ft.L.
CONTRAST	15 : 1
RESOLUTION	
• Background	9 arcmin per pixel
• AOI	1.5 arcmin per pixel
SERVO PERFORMANCE	
• Azimuth	580 °/sec 40,400 $°/sec^2$
• Elevation	490 °/sec 26,900 $°/sec^2$

FIGURE 7.15 VSCDP SYSTEM PERFORMANCE GOALS

One advantage of the VSCDP AOI approach is that only the EHT unit needs mounting on the pilot's helmet, adding only 5 or 6 ounces of mass and minimal inertia. A second advantage is that great care can be dedicated to the fixed blend region of AOI and background channels; no dynamic blending is required.

Problems also exist, one of which is that the entire visual field is being slewed about rather than just the smaller, less visible AOI channel. Until proven otherwise, this has a potential for enhancing AOI-related slewing artifacts. Also of concern is the issue of the Instructor's Operating Station (IOS). Visually repeating either the background or AOI channel at the IOS makes no sense if the images are jumping at rates corresponding to thousands of degrees per second. Getting image information to the instructor thus entails separate IG channels dedicated to IOS display. Alternatively, simple, lower-cost graphics displays could be utilized that present data on aircraft position, attitude relative to the ground, and important scene objects.

8.0 Summary

The attempt here has been to impart an understanding of the physical principles involved and equipment available for assembling display systems to support flight simulation training of CGI-based systems. Discussed were parameters used to characterize display performance and how these are measured in a practical sense. No single system, whether virtual or real, came out the winner. Each has associated with it certain advantages and disadvantages, and sometimes even risk concerning its workability. So long as this vagueness concerning display suitability persists, it will be necessary to carefully consider the training desired and resources available for a simulator before choosing a display system which, though sorely compromised, can and should be optimized.

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