Projection Displays

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Projection Displays

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Edward H. Stupp and **Matthew S. Brennesholtz**

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We dedicate this book to our wives
Bobby Stupp and Libby Brennesholtz

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Foreword

Projection Displays is the third volume in the Display Technology series published by John Wiley & Sons in collaboration with the Society for Information Display.

Projection displays have existed since before the invention of the cinema, but it is comparatively recently that there has been rapid development of electronically addressed projection display technologies and literally an explosion in their successful commercialization.

This book is the most comprehensive yet offered on this increasingly important subject. It is structured in a way which makes it readable straight through or as a source of information on a particular aspect of the subject. Part 1 is an overview of markets and applications which will help those not familiar with the subject to place it in context and perspective. Parts 2 and 3 cover technical aspects of all the components of projection displays. Part 4 deals with the systems aspects of architecture and performance. The final section deals with display characterization and artifacts. Four appendices cover the basics of radiometry and photometry, colorimetry, the often misunderstood subject of étendue and a glossary. It will be an invaluable source of information for scientists, engineers and technicians working in the field of projection display technology and projection display product development as well as for those who need to understand the strengths, limitations and differences in performance between different projection display technologies for the purposes of specification and purchase. Extensive references are provided for those who wish to read more widely or more deeply on the subject.

I welcome the addition of Projection Displays to this Display Technology series which has the objective display technology and its associated fields with volumes which are both technically rigorous and full of useful practical information.

Anthony C. Lowe
President, Society for Information Display
Greenock, 1998

Preface

The cinema projector is perhaps the most familiar projection display to the average person. This type of projector is capable of producing a large, high resolution image viewable by a large audience. Other common types of film projectors are slide projectors and viewgraph projectors. Unfortunately, all film projectors have a flaw: they require a film with stored images to project. Generating film images is time consuming and expensive. Today, the emphasis is on time and cost, and a more flexible, cost-effective replacement technology is needed.

Direct view displays with electronic input are also quite familiar to the average person. The most common direct-view displays are the cathode-ray tubes (CRTs) in television receivers and computer monitors. Other direct-view technologies, such as plasma displays and liquid crystal devices, are starting to compete with the CRT. All these displays are capable of high resolution and satisfactory luminance, but they in turn have a serious problem: it is difficult and expensive to make a direct-view display large enough so an audience of more than a dozen or so can view it simultaneously.

Electronic projection displays can have many of the best features of both film and direct view electronic displays. Potentially, electronic projection displays are as capable of generating images as large, bright and high resolution as film projectors can make. They are also potentially cost effective and competitive with direct-view displays. The projection display industry is working hard to build projection displays that meet these potentials. Size, purchase cost and operating cost are dropping rapidly as new models and new projection technologies are introduced. Resolution, image size and luminance are increasing rapidly, even while cost and projector size are decreasing.

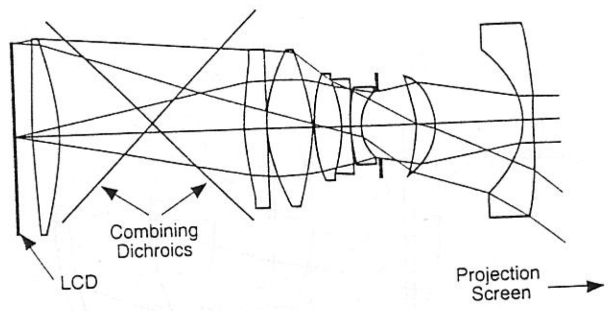

Figure 7.51 Typical three-panel LCD projection lens.

combines the blue, green and red beams. Therefore, this element must be replicated in each channel. Similar designs put a field lens directly adjacent to the LCD itself. In any lens where there are duplicated optical elements, it is necessary to ensure that the magnification, distortion, etc. of all three paths are the same.

When it comes to converging a three-panel system, mechanical x–y adjustment of two of the panels is used to align the screen image of a single point on each panel (normally the center) with the corresponding point on the third panel. In practice, the two adjustable panels must have full six-axis adjustments, three translational (x, y and z) and three rotational (θ, ϕ and ψ). If the three optical paths have the same magnification and distortion, then the entire image can be brought into convergence. If there is a magnification or distortion difference between the three optical paths, it will be impossible to achieve convergence everywhere in the image.

This convergence issue is one of the reasons why three-lens pixelated light valve projectors are not common. Three-lens CRT projectors can distort the raster electronically to correct for differences between the three lenses. In fact, this must be done, in order to correct the trapezoidal distortion of the off-axis tubes. Raster addressed light valves such as the Hughes/JVC, the Talaria or the Eidophor can also correct for the difference between lenses by adjusting the raster geometry. For a pixelated light valve, this is not possible and the lenses would have to be very closely matched for a three-lens projector to be acceptable.

7.6.3 Zoom lenses, focal length and throw ratio

One feature desired by projector manufacturer marketing departments that makes designing a projection lens more difficult is making the lens a zoom or vari-focus lens. Both of these lens types allow a variable image size to be projected on a screen. This allows the projector to be placed in a convenient

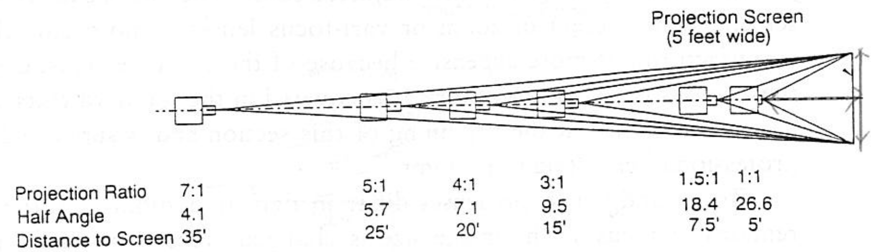

Figure 7.52 Throw ratios for projection lenses.

general guide, especially when combined with an ANSI lumen specification. However, since it says nothing about the distance to the screen, it says nothing about the projection lens.

Examples of various throw ratios are shown in Figure 7.52. A lens with a throw ratio of 1:1 would be a very wide angle lens that would produce an image whose width would be the same as the distance from the lens to the screen. A 1:1 lens would normally be used in a rear projection application. A 7:1 lens would have a long throw distance between the lens and the screen. This would allow a projector to be set up in the back of a large auditorium behind the entire audience and fill a screen large enough to be seen by everyone. Projection lenses with throw ratios of about 3:1 are the most widely useful. They are especially suitable for small conference rooms where the projector will be placed on the conference table and used to project on a screen at one end of the room.

With a throw ratio type of designation, an end-user can more easily get a feeling for how a particular projection lens would be used than with a focal length designation.

7.6.4 Projection lens offset

Another projection lens feature desired by marketing departments that makes design of a lens more difficult is the ability to offset the lens in order to project an image above the optical axis. This is shown in Figure 7.53.

In Figure 7.53(a), the front end of the projector has been tilted up in order to project onto a screen above the projector. This causes two problems. First, the focus of the image at the top and the bottom of the screen will be different, and it may not be possible to get both areas in focus at the same time. Secondly, and more importantly, trapezoidal distortion will be induced in the image, and the top of the image will be wider than the bottom of the image.

In Figure 7.53(b), a projector has been placed horizontally on a table and the lens has been offset in order to project the image above the centerline. In this case, there is no trapezoidal distortion from the lens position, and the image size then adjusted so that the image exactly fills the screen. While design of zoom or vari-focus lenses is more difficult, and manufacturing is more expensive because of the extra elements, design of these lenses is a well-known art. It is covered in the standard texts on lens design mentioned at the beginning of this section and is supported by all professional lens design programs.

Zoom and vari-focus lenses differ in that, in a zoom lens, the image remains in focus as the image size is changed. This is normally accomplished by a variable-cam mechanism designed into the lens that moves two or more elements or groups to automatically adjust focus as the lens is zoomed. This cam mechanism is missing from a vari-focus lens: after the image size is changed, the operator must manually refocus the image. The zoom lens is more expensive due to the extra mechanical and/or optical elements. With a zoom or vari-focus lens, the projector user gets a much wider choice of where he can set up the projector relative to the screen than would be possible with a fixed focal length lens, or even with a series of fixed focal length lenses.

Lenses for projection and other applications are normally designated by their focal lengths. For instance, a zoom lens for a 35 mm camera might have a range of focal lengths from 35 mm to 85 mm. This would mean a variation from a moderate wide angle lens to a moderate telephoto lens. Designating a lens by its focal length is only meaningful if the size of the object is known. For a 35 mm camera, the size of the film is 24 × 36 mm, or 43.3 mm diagonal, and most regular users of cameras learn intuitively what focal length corresponds to what magnification of the image on the film.

In projectors, the focal length of the lens is a less useful way of designating the lens because there is a wide variety of light-valve sizes in use, from a lower limit of less than about 13.7 mm (for VGA DMD devices) to an upper limit of about 250 mm diagonal for some matrix type single light-valve projectors made with panels from laptop computers. A more useful way to designate a projection lens is by the ratio between the distance to the screen and the width of the image on the screen. This ratio is sometimes called the 'throw ratio'. Terminology is not standardized; it can also be called 'projection ratio', 'projection factor', 'lens factor' or some other term involving 'throw', 'projection', 'lens' or 'ratio'. Unfortunately, these same terms are sometimes used in slightly different combinations to designate a zoom lens: it is necessary to understand exactly what is being specified when reading marketing literature.

Projector manufacturers often designate how large a picture the projector is capable of making, for example, 'screen sizes from 20 inches to 300 inches (measured diagonally)'.[*] This sort of information is useful as a

[*] From Mitsubishi G1A LCD Video/Data Projector literature.

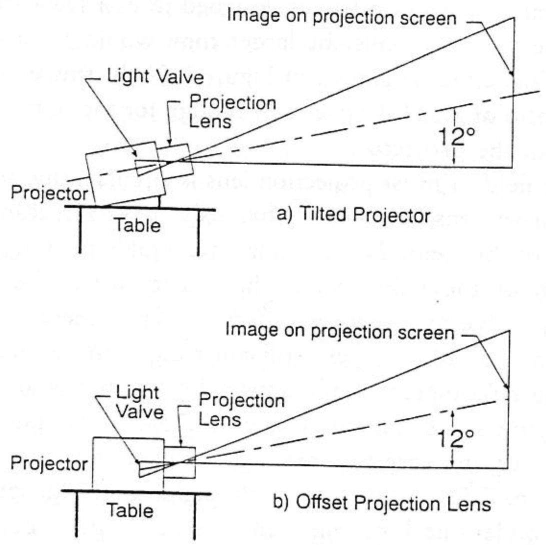

Figure 7.53 Application of an offset projection lens: (a) tilted projector; (b) offset projection lens.

offset, and the image will remain rectangular on the screen. Currently, the maximum practical amount of offset that can be designed into a projection lens is about 12°, as shown in Figure 7.53(b). This is sufficient offset to allow a lens with a throw ratio of 1.8 : 1 to produce a 4 : 3 image at the screen where the bottom of the image is at the level of the projector.

This feature is particularly desirable, although difficult to implement, in zoom lenses. If the bottom of the image starts level with the projector, as the lens is zoomed the bottom of the image does not move. As the image gets larger, the bottom remains at the same place on the screen while the top rises and the sides move out. This makes it particularly easy to set up a portable projector in a variety of conference rooms. It also means that as the image size increases there is no problem with the table top obscuring the lower edge of the image.

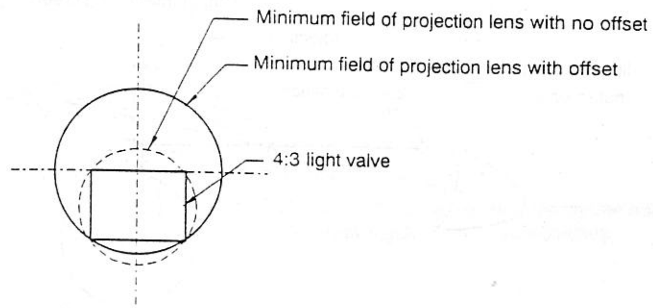

Figure 7.54 Field utilization with projection lens offset.

When a projection lens is designed to be used with offset, the field of the projection lens must be larger than would be used if there were no offset. This effect is shown in Figure 7.54. In this example, a lens with a throw ratio of 1.8 : 1 is offset 12°, enough for the bottom of the image to be level with the projector.

The field of most projection lens is circular, due to the circular nature of common lens elements. Obviously, a 4 : 3 rectangle can only use a portion of this field. The minimum acceptable field diameter is equal to the diagonal of the light valve. This occurs when the lens is centered on the light valve and there is no offset. When there is an offset, as shown in Figure 7.53(b), the field still must cover the entire light valve. In this case, the field increases in diameter by a factor of $\sqrt{2}$ and the area of the field doubles, as shown in Figure 7.54. This increased field size can significantly increase the cost and complexity of the lens.

Figure 7.53(b) shows how the light valve, the principal plane of the projection lens and the image on the screen remain parallel to each other as the lens and the image are offset. This is called the Scheimpflug condition. Note in Figure 7.54 only the bottom half of the field is used to project above the axis. If the lens mount is designed to allow full x–y adjustment of the projection lens, it is not only possible to place the projector below the center of the screen, but it is possible to place the projector above or to

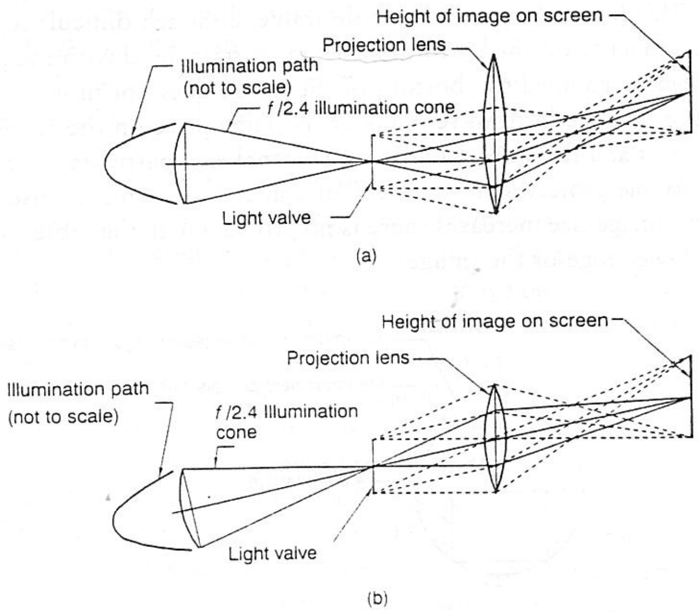

Figure 7.55 Illumination paths with projection lens offset: (a) lens offset without illumination path offset; (b) lens and illumination path offset.

one side of the screen without inducing trapezoidal distortion. In this way, a projector can be ceiling mounted and projecting down 12°, or mounted in a corner of the room and projecting to the left or right side. In this case, the top half or the right or left side of the lens field will be used.

Figure 7.55 shows the relationship between the illumination path (not to scale), the light valve, the projection lens and the image on the screen. Figure 7.55(a) shows the normal lens offset technique. In this case, the illumination path axis is perpendicular to the light valve and remains telecentric. The illumination path is *f*/2.4 in this example, with a cone of ±12°. This axis of this cone is parallel to the axis of the projection lens, so the lens also sees a cone angle of ±12°. Therefore, the lens *f*/# is still *f*/2.4.

In Figure 7.55(b), the situation is changed. The illumination path is tilted relative to the light valve by the same amount as the lens offset. One thing this accomplishes is that the field increase requirement shown in Figure 7.54 no longer applies: the field needs to cover only the light valve and no additional area. On the other hand, the *f*/# of the lens must be reduced. While the cone angle of the light relative to the illumination system is still ±12°, relative to the light valve or projection lens the angles go from 0° to 24° in this example. Off-angle light rays of 24° require an *f*/1.23 lens axis to be transmitted. In this case it is the pupil that is under-utilized, not the field, as shown in Figure 7.56.

The design shown in Figure 7.55(a) is far more common than the arrangement in Figure 7.55(b). There are several reasons for this. The main reason is that in Figure 7.55(a) only the projection lens needs to be moved on an x–y stage if the designer desires variable offset. In Figure 7.55(b) it would be necessary to move both the lens and the illumination path to achieve variable offset. Moving the illumination path would involve not only a translation, but a tilt change as well.

Another reason for preferring the arrangement in Figure 7.55(a) over 7.55(b) is contrast of most light valves is a function of the angle the light passes through the light valve. In Figure 7.55(a), the maximum angle is 12° but in Figure 7.55(b) the maximum angle is 24°. Therefore, for most light-valve types, the arrangement in Figure 7.55(a) would show better contrast.

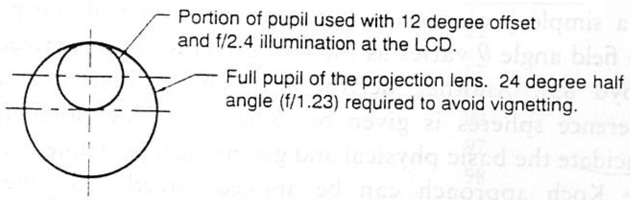

Fig 7.56 Pupil utilization with a tilted illumination path.

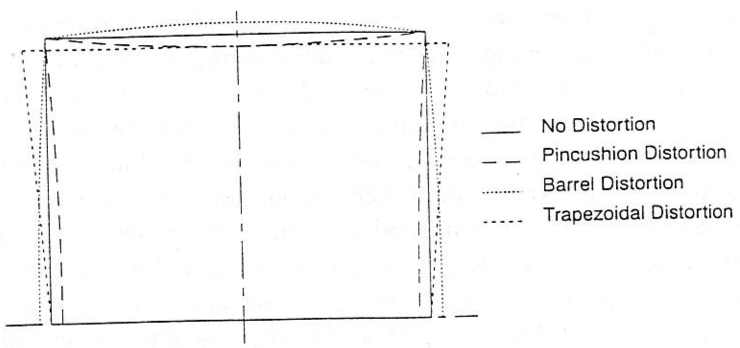

Figure 7.57 Distortions with image offset from the horizontal.

If a light valve requires a tilted illumination path, the arrangement in Figure 7.55(b) might be preferred. For example, the DMD requires 20° off axis illumination and this arrangement may be preferred. Some LCD designs also perform better with off-axis illumination and this technique might be preferred.

If the lens has any inherent distortion such as pincushion or barrel distortion, this will affect the image whether the lens is offset or not. The effect will be more severe with lens offset, however, because higher field angles or lower *f*/# lenses are used. Also, with enough offset to allow a projector to sit flat on a table and not have the image obstructed by the edge of the table, the lower edge of the image goes roughly through the center of the lens. The top of the image goes through the edge of the lens and sees a different distortion. Therefore, the top and bottom edges of the image may not be parallel.

In Figure 7.57 these various distortions are shown for a 4 : 3 image, when there is sufficient offset to allow the image to be level with the table top on which the projector is sitting. Clearly, the rectangular image with no distortion is preferred if it can be achieved in a cost effective lens design.

7.6.5 *Matching the projection lens to the illumination optical path*

In a simple projection system, the luminance of the projected image at the field angle θ varies as the $\cos^4(\theta)$. This law is derived, for example, in [Boyd 83]. Another derivation using a different approach involving reference spheres is given by [Koch 92]. The Boyd approach helps to elucidate the basic physical and geometrical principles of radiometry while the Koch approach can be applied directly to other luminance and throughput problems associated with projectors.

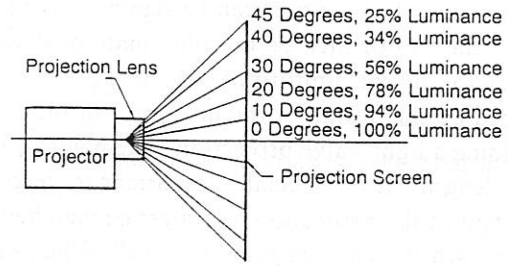

Figure 7.58 $\cos^4$ law.

The $\cos^4$ law is illustrated in Figure 7.58. This law applies most directly to CRT projection sets with flat CRT faceplates. The $\cos^4$ law is not absolute. Manipulation of the pupil position and shape during lens design can reduce the center to edge fall off relative to the $\cos^4$ law. A curved faceplate [Wolf 37, Malang 89] or an IARC CRT [Vriens 88; Clarke 88b] design can also modify the light falloff predicted by the law. With realistic, manufacturable designs for CRT projection lenses, however, the $\cos^4$ law is a moderately good predictor of the center to edge fall off in luminance of a CRT projection system.

For a given lens throw ratio and image aspect ratio, the field angle to the corner of the screen can be calculated. Knowing the field angle, the luminance at the corner can be estimated from the $\cos^4$ law. The results of this calculation are shown in Table 7.1 for 4 : 3 screens. As can be seen, for high throw ratios (long focal length lenses), 3.0 : 1 and higher, the luminance fall off from the center to the corner of the screen due to the $\cos^4$ law is not significant. For low throw ratios, this effect can be the major factor reducing the corner luminance compared to the center.

The $\cos^4$ law does not necessarily apply to light valve projectors. It has been shown [Shimizu 95] that if the *f*/# of the projection lens is lower than the *f*/# of the illumination path, the $\cos^4$ law no longer applies and the

Table 7.1 Relative luminance at corner of screen due to $\cos^4$ law.

Throw ratio	Angle (to corner) (degrees)	$\cos^4\theta$ (%)
0.63	45.0	25
1.00	32.0	52
1.50	22.6	73
3.00	11.8	92
5.00	7.1	97
7.00	5.1	98
10.00	3.6	99