

Optics for Reflection Holographic Stereogram Systems

by

Eric P. Krantz

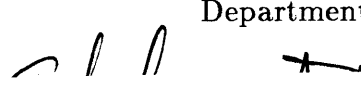
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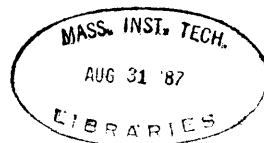
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Submitted to the Department of Architecture on August 13, 1987 in
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Abstract

Recent optical and computer graphic methods have produced the "alcove" holographic stereogram that is capable of reconstructing in laser light an undistorted 3-D projected image from a series of 2-D views on a concave surface. This technique requires only one holographic step to obtain an undistorted real image stereogram, formerly accomplished by two separate holographic procedures. The holographic stereogram is desirable in a form that permits white light reflection viewing of the holographic image. The optical design and construction of a reflection holographic stereogram system is herein presented.

Thesis Supervisor: Stephen A. Benton
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Contents

1	Introduction	7
2	Historical Stereogram Development	9
2.1	Stereo Pair Viewing	9
2.2	Holographic Stereogram Development	11
2.2.1	Early Developments in Integral Holography	11
2.2.2	White Light Techniques and Viewing Distortions	16
2.2.3	The Alcove Format	24
3	Reflection Holographic Stereogram System Design	26
3.1	System Overview	26
3.1.1	Imaging and Reference Beam Systems	27
3.1.2	Illumination and Viewing Geometry	31
3.1.3	Image Processing Procedure	34
3.2	System Optics Selection	35
3.2.1	Image Beam Optics	36
3.2.2	Reference Beam Optics	39
4	Optical Construction of the Reflection Holographic System	41
4.1	Cylindrical Holographic Optical Element	41
4.2	Spherical Holographic Optical Element	45
4.3	The Flat Format Holographic System	47
4.4	The Alcove Format Holographic System	47
5	Experimental Results	50
5.1	Primary Tests	50
5.2	Modifications and Secondary Tests	52

5.3	Alcove Test Results	57
6	Conclusions and Future Directions	59
6.1	Image Quality Improvements	60
6.2	Large Scale Images	60
6.3	Efficiency Predictions	61

List of Figures

3.1	The imaging system.	28
3.2	The reference beam system.	30
3.3	Alcove illumination geometry.	32
3.4	Flat and Alcove format viewing geometry.	33
4.1	Cylindrical Holographic optical element setup.	43
4.2	Spherical Holographic optical element setup.	46
4.3	Flat format holographic setup.	48
4.4	Alcove format holographic setup.	49
5.1	Initial lenticular orientation.	53
5.2	Modified lenticular orientation.	53
5.3	USAF 1951 resolution target in flat format reconstruction.	55
5.4	“Sanji-gen” in flat format reconstruction	56
5.5	“Test pattern” in alcove format reconstruction	58

Chapter 1

Introduction

The need for autostereoscopic three dimensional visual representation provides the basic impetus for the holographic stereogram—a series of 2-D views combined to produce a 3-D image. While the holographic image requires no viewing aids, restrictions are imposed upon an observer that are absent in real object perception. Research aimed at relaxing these restrictions is clearly worthwhile, it is a progression toward eliminating perceptual differences between tangible and imaginary scenes.

The ideal 3-D image could be seen in full color over a wide horizontal and vertical angle of view, would contain full parallax information, and would also be capable of animation. The system that presents this image should not require any viewing apparatus or specialized illumination source. It should be capable of producing the image on a large scale and in a short amount of time.

The “alcove” format hologram is a development along this line. It projects a 3-D image that appears to “float” in space and it can be seen by

many observers at once over a near 180 degree angle of view. The alcove holographic stereogram entails a two step production process that merges computer graphics with holography. This process accomplishes in one holographic step an undistorted real image (in front of the hologram plane) that formerly required two holographic steps. This simplified holographic procedure is particularly appealing in the context of a fast, computer peripheral laser printer device for 3-D output.

The applications for a 3-D computer peripheral include medical imaging, and computer aided design of architectural, automobile, and numerous other structures. The device would also be useful in media presentations for advertising and artistic purposes.

The current system is not yet a fully automated computer peripheral, but it is a progression along those lines. Previous optical techniques required coherent illumination (laser light) of the alcove hologram [2]. However, it is more practical to be able to reconstruct the image with ordinary white light illumination. Moreover, it is desirable to construct a volume type (reflection) rather than transmission type hologram. The lighting geometry is simplified in the case of a reflection hologram, and the color is more consistent over an increased viewing range. Thus, we proceed with the goal of optically constructing a reflection holographic stereogram system capable of producing alcove format images from computer generated scenes in one holographic step.

Chapter 2

Historical Stereogram Development

2.1 Stereo Pair Viewing

The most basic concept of the holographic stereogram is the principle of stereo pair viewing, first described by Sir Charles Wheatstone in 1838. Wheatstone realized that two 2-D perspective views can give the combined appearance of a 3-D scene. The perspective views can be obtained from photographs, graphic illustrations, patterns, or any display device, but need to be carried out by means of a specially tailored viewing system. Effective systems must present each eye with the corresponding image perspective, without substantial crosstalk, and in a manner that enables comfortable binocular fusion of the scene. In general, system designs require the observer to peer through a specially constructed stereo-viewing aid or they are optically integrated so that the correct views are “automatically” presented

to the unaided eyes in a narrowly restricted area.

In order for an observer to comfortably “see” the paired images in 3-D, it is essential to carefully choose the recording geometry based upon the final viewing parameters of the system. These include scene depth, viewing distance, angular position, and inter-ocular spacing. The viewing parameters are related by the geometrical calculations of the disparity budget, a quantitative guide to the parallax limits between the simultaneously observed views. The equations describing these characteristics are as follows:

$$\Theta_{near} - \Theta_{far} = 1.25^\circ \quad (2.1)$$

$$\frac{1}{d_{near}} - \frac{1}{d_{far}} = \frac{1}{\text{I.O.D.} * 46} \quad (2.2)$$

where Θ_{near} is the angle subtended by the eyes to the nearest point of the scene, Θ_{far} is the angle subtended by the eyes to the farthest point of the scene, d_{near} and d_{far} are the distances from the view plane to the respective points of the scene, and **I.O.D.** is the interocular distance.

Thus, one method to determine the recording positions of corresponding right and left eye views can be found by using the standard inter-ocular spacing of 6.25 cm and measuring the near and far distances of the scene to the observer. The playback system must then maintain a geometry similar to the recording step in order to preserve the correct aspect ratio and to ensure undistorted binocular fusion of the scene at the intended viewing distance.

2.2 Holographic Stereogram Development

The holographic stereogram is a system capable of synthesizing any number of stereo paired views and presenting them to an observer without the need for specialized viewing aids. From a historical perspective, one can trace the lines of development from a succession of inventive imaging techniques. Holographic stereography has evolved from monochromatic laser viewable images of cinematic recordings to white light viewable full color images of computer rendered scenes. In the process, the recording stage of the subject matter has gained a more advanced role in the imaging and playback systems, from the function of accurate replication of solid objects to distortion compensation of imaginary computer generated scenes. Recording, imaging, and playback steps now have more complex relationships, and integrate greater specialization into a unified system design.

2.2.1 Early Developments in Integral Holography

A two-step method for making integral holograms of real 3-D objects viewable in white light was first described by R.V.Pole [18] in 1967. In the initial stage, the object was illuminated with ordinary white light, and a photographic record was taken through a fly's eye lens array located at the film plane. The fly's eye elements captured the object rays in unique directions and focused them onto the film. The developed film served as the "holocoder" or transparency for construction of a Fresnel type hologram in the second step. The integral transparency was placed against the fly's eye array and illuminated with a coherent source to project back rays with

a unique correspondence to rays collected in the initial object recording. The projected rays formed a real 3-D image in the original object location. A holographic plate located near the real image plane was interfered by a reference beam to produce a volume hologram capable of white light reconstruction. When reconstructed with the original reference beam, an observer could view a 3-D virtual image from the perspectives recorded by the fly's eye elements. The density of the array determined the sampling of views. One problem of the technique was that it required a tightly packed lens array in order to reduce the "dead space" between focused points on the hologram. This area of the hologram plate was inactive, and caused the image to appear discontinuous. Transmission type holograms made from this method were subject to spectral blurring, and could be sharply resolved only with a monochromatic source.

Another method of integral holography was proposed by J.T. McCrickerd and N. George [16] in early 1968. The subject matter remained limited to solid 3-D objects, but the important aspect of the process described a step and repeat sequential recording of the hologram. Instead of using a fly's eye array for simultaneous recording in each step, the technique utilized a lens-pinhole design to capture and playback the discrete directional rays of the three dimensional subject. In the first stage, the object was illuminated with an incoherent source masked by a pinhole placed between it and the photographic emulsion. The pinhole permitted only a fraction of the object rays to pass through, corresponding to the angle of view. The rays were in turn imaged by a convex lens, and recorded at the film plane. The pinhole mask was translated, and the process repeated to produce adjacent

angles of view. In the second stage, the master photograph was illuminated with laser light and imaged by a lens onto holographic film, which was masked again with a pinhole aperture, and interfered with a reference wave. The subsequent step and repeat process yielded a holographic stereogram, viewed orthoscopically with the phase conjugate (“time-reverse”) of the reference beam.

The fly’s eye and pinhole camera systems posed a practical difficulty in the 2-step synthesis, for they required a large number of 2-D views (an n by n array) to produce a 3-D image. In the United States, D.J. De Bitetto [5] in 1968 presented a system that sacrificed vertical parallax in favor of reduced bandwidth processing. The method allowed for horizontal parallax only viewing, and was described as a “3-step” procedure. The 3-D subject was initially recorded in noncoherent light as in the previous citations, yet in this instance, a linear lens array (lenticular array) served as the imaging apparatus. The second stage imaged the integral photographic views onto holographic film, and the third stage converted the views into a horizontal “strip hologram” using a moving hologram plate masked by a stationary slit aperture. The holographic stereogram created was a transmission type, and viewable only in laser light. When illuminated with the original reference beam, the eyes viewed a 3-D virtual image through the corresponding strips of 2-D views of the hologram. The salient feature in this new method was the use of a slit as the means for multiplexing the perspective views. Despite the introduction of the lenticular array, the first stage remained a drawback in that, like Pole’s method, it limited the sampling of the scene to the density of the lens array.

Concurrently in the United Kingdom, J.D. Redman and W.P. Wolton [19][20] in 1968 described a technique for multiplexing a series of 2-D views taken from a cinematographic camera. The method was also horizontal parallax limited, by virtue of the initial recording stage. More important, the cine camera did not use a linear lens array, and was capable of tracking any panoramic scene in sequential exposures. In the first stage, the camera translated in an arc about a subject, taking pictures at a constant rate. In the second stage, one frame was magnified and projected by an afocal lens system onto a holographic plate. Interference with a reference beam created a transmission type hologram of the imaged transparency. The process was repeated for the remaining frames by advancing the cine film, rotating the plate about its center, and rotating a mirror on the reference leg. This procedure enabled each transparency to be imaged at a different angle to the plate, yet maintained a constant reference angle for all elements. When the developed plate was illuminated with white light and seen through a converging lens, each 2-D composite element reconstructed on the hologram plane at a slightly different angle to form a 3-D virtual image. The clear benefits of this technique were that the number of synthesized components could be extended beyond the practical limits of a lenticular lens array, and reconstructed with noncoherent illumination. A later improvement eliminated the need for viewing through a convex lens [21]. The hologram was instead made with a converging reference wave and was played back with a plane reference wave to introduce curvature in the reconstruction. However, there were also practical drawbacks to the system. Each exposure was overlapped with all the others, causing incoherent “bias buildup” in

the film, which significantly reduced the hologram's diffraction efficiency. So, an increase in views entailed an decrease in brightness. The holographic image also suffered from keystone distortion, an aspect ratio change evident from viewing linearly a series of views recorded in an arc.

In 1969, research in Japan by Kasahara, Kimura, and Kawai [13][14] and by De Bitetto [6] in the United States integrated motion cine camera recordings into a more practical system design. The motion camera took views along a linear path, which were then projected sequentially onto a diffusion screen. A translating slit aperture located at the film plane allowed the elements to be synthesized as adjacent strip holograms without overlapping. The "bias buildup problem" was thus circumvented. Reconstructed with the original reference wave, each hologram strip formed a 2-D virtual image in a location identical to its previous projection onto the diffusion screen. When all the hologram strips were reconstructed, the unique locations of the composite elements, corresponding to the views taken by the movie camera, converged to form a virtual 3-D image. An observer scanning the composite hologram horizontally would therefore view a 3-D image containing all the parallax information recorded from the original scene. Because the perspectives were gathered, multiplexed, and viewed in a linear translation, keystone distortion was eliminated.

A drawback to this technique was reduced photographic film resolution. The linearly translating camera took views that were not "scene centered" as in Redman's method, so each frame had to be under-filled in order to record a central point of interest over the paraxial range. As an alternative to the flat format, Kasahara, Kimura, and Kawai [14] proposed a cylindri-

cal format which maintained full-frame resolution. Yet, a major drawback remained, for the holographic stereograms required monochromatic illumination in order to produce sharp images.

2.2.2 White Light Techniques and Viewing Distortions

In 1970, M.C. King, A.M. Noll, and D.H. Berry [15] introduced a method for making transmission holographic stereograms that could be viewed in white light. They realized that the spectral blurring effect on transmission images could be eliminated by making a second generation image plane hologram from De Bitetto's diffusion screen projection type composite hologram. Because each view of the composite was projected at unique locations onto a single plane, namely the diffusion screen, each element would reconstruct with coherent light a focused real image at that same plane. A holographic plate placed at this real image plane could capture all the projected views simultaneously. The resulting second generation hologram contained the entire parallax information of the strip master. In essence, the image plane of the original strip hologram had been translated from some distance in front of the plate (the distance to the diffusion screen) to the surface of the plate. The "copy" reconstructed each 2-D image sharply in white light precisely because spectral blurring is eliminated for image points located at the hologram plane. When the copy hologram was illuminated with its phase conjugate, the adjacent strips of the composite master would be projected towards the eyes of the observer to form

the viewing zone. The observer would “see” the 3-D real image through adjacent strips corresponding to the right and left eye perspective views.

The white light transmission stereogram had important advantages over its predecessors. The images of transmission type holograms reconstructed brighter than those of volume type white light holograms given the same intensity because the incident light diffracted over the entire visible spectrum, not just in one narrow wavelength. And, there was no “bias buildup” because all the views of the copy were exposed at the same time with a single reference beam. The one-step image plane exposure was also more valuable in terms of efficient production; from one composited strip hologram, any number of copies could be made without needing to replicate the step and repeat sequence.

Aside from the holographic copying stage, the new method integrated the use of computer rendered graphics into a unified system design. “Computer generated holography” was the title given to describe the computer graphics to 3-D hardcopy procedure. By means of this procedure, the perspective views of a wholly imaginary 3-D scene could be generated by a computer, stored in memory, and sequentially recorded by a movie camera from a standard CRT device. This approach not only extended beyond the capabilities of panoramic recordings of real subjects, but sparked a new avenue of holographic stereogram applications. A 3-D subject could be designed and realized in white light holographic form totally within the laboratory setting without the 3-D subject ever having existed as solid matter. The technique also provided greater mechanical control over the real scene recordings in terms of registration and precise angular view.

Still, there were drawbacks in both the computer and optical stages. The current capabilities of computing power required an enormous amount of time to render a complex, highly detailed scene. And, the image resolution of the CRT monitor was not as great as a real subject recorded directly on movie film. In the holographic compositing stage, the diffusion screen introduced granularity in the image corresponding to the coarseness of the projection screen. Consequently, a trade-off existed between the optical system efficiency and image quality. The horizontal viewing zone was limited to the physical size of the strip master plate. In order to achieve perfect phase conjugate illumination, and hence an undistorted image reconstruction, it was an optical practicality to construct the master with a collimated wavefront. It could then be accurately played back with a collimated wavefront from the reverse direction, rather than using a diverging / converging reference scheme. This meant however, that a large collimating lens or mirror, or a very great throw distance was required for the reference beam path in the compositing step and for the subject beam path of the copy step. Since the master plate could only be as large as the diameter of the collimated beam, the viewing zone range was therefore limited to the physical size of the collimating optic. Despite tremendous benefits in design applications, the combined system entailed a more complex, 3-step procedure. In addition to the computer rendering and CRT recordings, the holographic process required two separate systems for the final real image product.

In 1973, L.G. Cross [4], an independent inventor, introduced a 2-step method for making cylindrical format holographic stereograms that could

be reconstructed in white light. With this technique, the field of view could easily be extended to 360 degrees. In the first step, a stationary movie camera took views of a rotating subject. In the second step, each frame was imaged onto a cylindrical lens, that then focused the image rays onto the holographic film sheet. A diverging reference beam passed through a slit aperture mask on the film plane to interfere with the focused image. The movie frame was advanced, the film sheet translated one slit width, and the adjacent strip exposed until all aspects of the original recording had been reproduced. This composite hologram was white light viewable because the final cylindrical lens acted to focus *only* the image rays in the horizontal dimension and therefore reduced bandwidth reconstruction in the vertical dimension. The color smear effect resulting from different vertical displacements and magnifications of the image in broadband illumination was thus eliminated. An observer viewed a Benton type rainbow image that changed color when scanned vertically, yet retained a sharp focus horizontally. Scanned in a horizontal rotation, the observer would “see” a 3-D image about a 360 degree arc, corresponding to the angular domain of the movie film recording. Each 2-D element reconstructed a virtual image at the location of its previous image focus on the cylindrical lens surface. Here, virtual image reconstruction had an important optical advantage. The hologram could be constructed and illuminated with a diverging wavefront, eliminating the need for a collimating element in the reference beam path. Therefore, an extended point source, namely a monofilament clear glass bulb, was an adequate means of illumination.

While the technique surpassed previous holographic stereogram systems

on several fronts, it introduced serious drawbacks in other aspects. The physical size and optical characteristics of the cylindrical lens determined the viewing limitations of the system. The final image could be no larger than the extent of its projected rays collected by the cylindrical lens. Hence, an increase in image size required a larger lens. The f-number of the lens determined the field of view of the composited hologram. Thus, both the physical size and the focal length of the cylinder were matters of concern. As the f-number decreased, the field of view increased. This relationship posed a practical difficulty, for a large, low f-number lens of good quality was extremely expensive to produce. An oil filled clear plastic cylinder lens could be inexpensively constructed, but tended to degrade image quality by introducing significant lens distortions, most notably spherical aberration. Cross's optical design of the imaging beam path also entailed astigmatism, a result of the different position of the horizontal focus component formed by the cylindrical lens from that of the vertical focus component.

In 1973, I. Glaser [8] presented an analysis of the distortions inherent in horizontal parallax only (HPO) holographic stereograms as a function of the recording and viewing geometries. In certain cases, a HPO stereogram was found to exhibit anamorphic imagery, defined as having different magnification of the image in each of two perpendicular directions. Glaser's analysis defined the anamorphic distortion as the ratio of the vertical to horizontal image magnification resulting from an originally undistorted (1:1 ratio) transparency. For the viewing case where the eye was located at the slit plane of the hologram, the anamorphic distortion was found to be unity (no distortion) regardless of the transparency's projected distance on the

diffusion screen to the composite hologram or the perceived depth location of the 3-D image. Glaser expressed the anamorphic distortion ratio as a function of the perceived image distance to the eye. As the eye moved away from the slit plane, the analysis showed three interesting cases:

1) For perceived image points in front of the diffusion screen projection, the vertical magnification increased faster than the horizontal magnification (distortion ratio > 1).

2) For perceived image points behind the projection plane, the horizontal magnification increased faster than the vertical magnification (distortion ratio < 1).

3) For perceived points located on the projection plane, the distortion ratio was found to be unity regardless of the viewing distance (distortion ratio $= 1$).

The anamorphic distortions of the first two cases were clearly observed as a linear aspect ratio change in the 2-D transparency. For example, a transparency of a circle would be viewed in the hologram as an ellipse. However, when a series of 2-D images were binocularly viewed, the distortion also produced a curvature effect in the perceived 3-D image; a line which bisected different image planes would seem to “bend”. The implications of anamorphic imagery uncovered serious drawbacks in image replication of previous HPO holographic stereogram techniques. In the 3-step method of King, Noll, and Berry, these distortions could be eliminated at the intended viewing zone because the eyes could view the image at the location of the projected slit plane without being brunt against the surface of the hologram. In the Cross 2-step method, however, anamorphic

imagery could not be eliminated (except in case 3 mentioned above which produced a totally “flat” image). This was because the exit pupil location was some distance away from the strip component at the hologram surface. Therefore, an observer viewing at the hologram surface would not be able to binocularly “fuse” the 3-D image.

In 1977, Glaser and A.A. Friesem [9] compounded the anamorphic analysis of HPO holographic stereograms to include “cylindrical distortion”. Glaser’s previous efforts described the relationship between the axial orthogonal recording and viewing positions only, that is, the points along the perpendicular to a flat projection screen. Unlike anamorphic distortion, cylindrical distortion arose from an angular displacement in the viewing of the HPO hologram different from the angular recording of the scene. An increase in this angular disparity was found to result in a more pronounced curvature of the reconstructed image. Another important aspect of this work demonstrated the use of pre-distorted computer plotted graphic images as the means to compensate for the distortions inherent in viewing the reconstructed image [10]. Yet, it is important to note that since the anamorphic and cylindrical distortions changed as a function of the viewing distance, precise compensation could be made for a specific viewing distance only.

S.A. Benton [1] in 1978 expanded the cylindrical distortion analysis for the Cross type hologram, and presented an optical recording scheme that corrected for the exhibited “web” curvature of the image without the need for computer graphics. Benton presented a ray traced analysis that demonstrated an increase in distortion corresponding to an increase in the

percieved image depth within the cylinder. In other words, the more area the image filled inside the cylinder, the greater would be the exhibited distortion. Benton noted that any pre-distortion scheme had to conform to an autostereoscopic rule, namely, the directions of rays recorded by a single frame of the camera must be the same as those reconstructed from a single element of the hologram. Thus, he proposed to record the rotating scene through a large cylindrical lens having similar optical characteristics to the lens used in the multiplexing step. At similar geometrical distances, the angular aperatures and image aspect ratios would therefore be matched. An important result of this technique permitted the percieved 3-D image to fill the cylinder area without exhibiting significant distortion. However, the necessity of a large, probably low f-number, cylindrical optic posed a serious impracticality for large scale images.

This intermediate period of holographic stereogram development had produced white light viewable HPO holograms using both 3-step and 2-step techniques. In the process, detailed analyses were given for the anamorphic and cylindrical distortions inherent in such images. Methods were demonstrated to correct for these viewing distortions by means of pre-distorting the original scene recording, either with optics or with computer generated graphics. The role of the unified recording / playback system had thus evolved to a highly specialized, more complex function. Yet, in order to acheive a real image projection which an observer could "grasp" in front of the hologram surface (much more convincing for realistic 3-D imagery) the method required two holographic steps. For the practical environment of a computer peripheral device, the 2-step technique posed an optical bottle-

neck. Moreover, the image plane copy method imposed greater limitations in the viewing zone of an observer.

2.2.3 The Alcove Format

In January of 1987, S.A. Benton [2] introduced the “alcove” format holographic stereogram, a 2-step technique for undistorted real image reconstruction that eliminates the need for a second holographic step. The alcove technique is a merger of computer graphics with holography that enables a near 180 degree field of view (compared to the standard 30 degree field of view for conventional real image techniques). Unlike previous cylindrical stereograms, the surface of the alcove defines a concave rather than convex curvature. An observer can thus “grasp” at the projected image without obstruction from the hologram cylinder. The image distortions exhibited by the alcove geometry are severe and must be compensated for by an image processing method. Computer generated images do not require auxillary optics for recording the original scene, and can be readily pre-distorted to anticipate the viewing distortions of the alcove hologram.

The alcove hologram was first produced in a form which requires laser illumination for reconstruction. While this simplification of the optical printing system has succeeded in demonstrating the concept of the recording / playback technique, it is certainly more desirable to produce an alcove hologram that can be sharply reconstructed in white light. Specifically, it is a greater advantage to construct a volume type rather than

transmission type hologram because the lighting scheme will be greatly simplified. Reflection holograms also display better color uniformity over a wider vertical viewing range. In the following chapter, an overview of the system is presented, in which the construction and reconstruction geometries and subsequent graphic image predistortion techniques are discussed in greater detail, leading to the optical design considerations for a reflection holographic stereogram system.

Chapter 3

Reflection Holographic Stereogram System Design

3.1 System Overview

The optical setup of the reflection holographic stereogram incorporates two features, the imaging system and the reference beam system. Although both are necessary for construction of the hologram, we first consider them as separate entities and give an overview of the functions we require from each system. These functions of the optics are related to the viewing and illumination geometries, respectively. Next, we show the correct direction and angle for lighting the hologram and describe what an observer actually “sees” in the viewing zone. Finally, we present an outline of the image processing procedure necessary for distortion compensation.

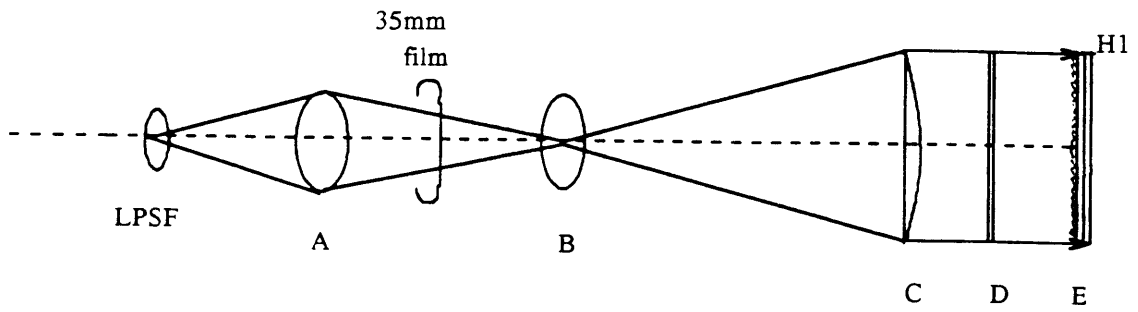
Here it is important to note that the system will be capable of producing flat format as well as alcove format real images. In either case, the imag-

ing system will remain the same. The reference beam system, however, will change in accordance with differences in lighting the holograms (both types remain white light viewable). In addition, each format will require a variation in the degree of graphic pre-distortion in the image processing step because each will display a different degree of image distortion as a function of the viewing zone. In both formats, we reconstruct the hologram with phase conjugate illumination, the “time reverse” of the reference beam.

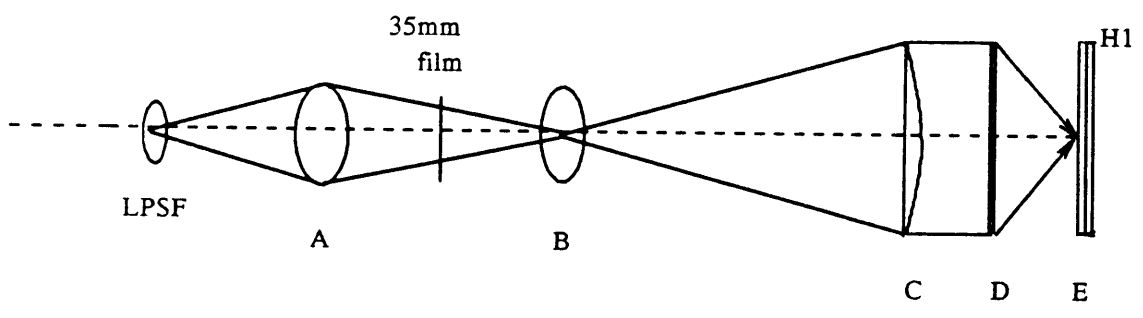
3.1.1 Imaging and Reference Beam Systems

Figure 3.1 is a representation of the imaging beam path of the holographic system. The function of the imaging system is to process the data, given in the form of a graphic transparency, in order to achieve a desired output at the hologram plane (the H1 plane). In this instance, we desire an output that is both magnified and at a sharp horizontal focus at H1. Because the hologram is a composite of many area-segmented vertical strips, we want the horizontal focus to be in the form of a vertical line. Hence, we first trace the system optical components and describe their functions up to character “D”.

“LPSF” represents a lens-pinhole spatial filter that expands the laser beam and removes residual noise from the lens. “A” represents a condensing lens that makes efficient use of the incident light in illuminating the 35 mm transparency, and focuses the light onto a point at the center of “B”. “B” is the imaging (or projector) lens that magnifies the image of the transparency



TOP VIEW



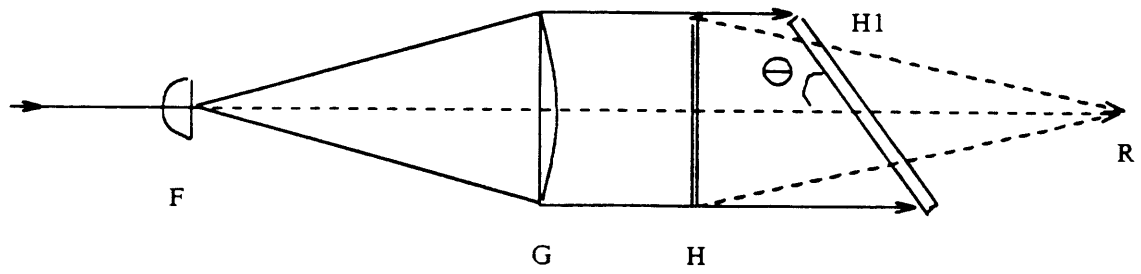
SIDE VIEW

Figure 3.1: The imaging system.

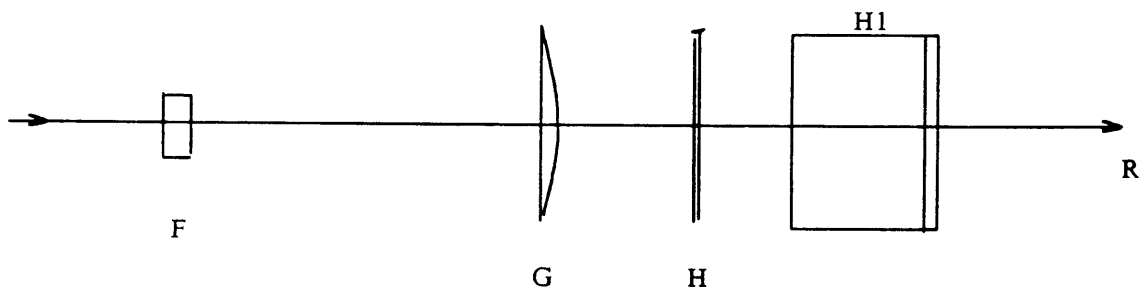
to a sharp flat-field focus at the surface of “C”. “C” is a collimating element that serves to project the image focus to infinity onto element “D”. “D” is a cylindrical element that in turn focuses only the horizontal component of the image onto the H1 plane. The image projection is orthogonal to the H1 plane.

Because we are constructing a reflection type hologram, which has an inherently narrow spectral reconstruction, we will need to include another key element in the imaging beam path in order to increase the vertical viewing area. In cylindrical rainbow type transmission stereograms, we recall that a change in the vertical viewing position produced a change in the observed color of the image. In the reflection case however, the color of the image will not appear to change dramatically with a change in vertical position; rather, the zone will be considerably narrowed to the vertical expanse of a specific output color. For this reason, we include element “E” at the H1 plane whose function is to diffuse the collimated vertical component of the image. “E” introduces an angular convergence for the otherwise parallel vertical image rays, and will maintain a sharp focus of the image at a position on the H1 plane. “E” acts to increase the viewing range at one narrow color output by causing the vertical image rays to diverge in a reverse direction when reconstructed with phase conjugate illumination.

Figure 3.2 is a representation of the reference beam path of the holographic system. The reference system function is to process unmodulated light to interfere with the image output at the recording plane. For the flat format, we desire a collimated reference beam at H1 in order to reconstruct the hologram with simplified phase conjugate illumination, namely, a plane



TOP VIEW



SIDE VIEW

Figure 3.2: The reference beam system.

wave (the sun serves as an excellent source). For the alcove format, we desire a more complex referencing scheme using a converging reference wave in order to playback with a diverging wave from a point source (an ordinary monofilament light bulb). In both these instances, it is clear that the reference beam must strike H1 from the opposite side of the emulsion than the imaging beam in order to form a volume type (reflection) hologram. With this general information in mind, we proceed with a component description.

“F” represents a cylindrical element, that serves to expand the incident undiverged laser light along the same axis (the horizontal dimension) as the image focal line. “G” is a collimating element that collimates the diverging beam in the horizontal dimension. For the flat format hologram, these two components constitute the reference system. The alcove format includes “H”, a converging lens element, that forms a point focus some distance beyond the H1 plane at “R”. In both flat and alcove reference cases, the angle incident to the H1 plane is 45 degrees.

3.1.2 Illumination and Viewing Geometry

In both the alcove and flat formats, we assume perfect phase conjugate illumination in accordance with the original reference angle and distance. In figure 3.3, the alcove hologram is shown illuminated by a point source “I”, at the same angle and location relative to the H1 surface as the focal point “R” of the reference beam in figure 3.2. In this illustration, the alcove is illuminated at a 45 degree angle from below the concave surface.

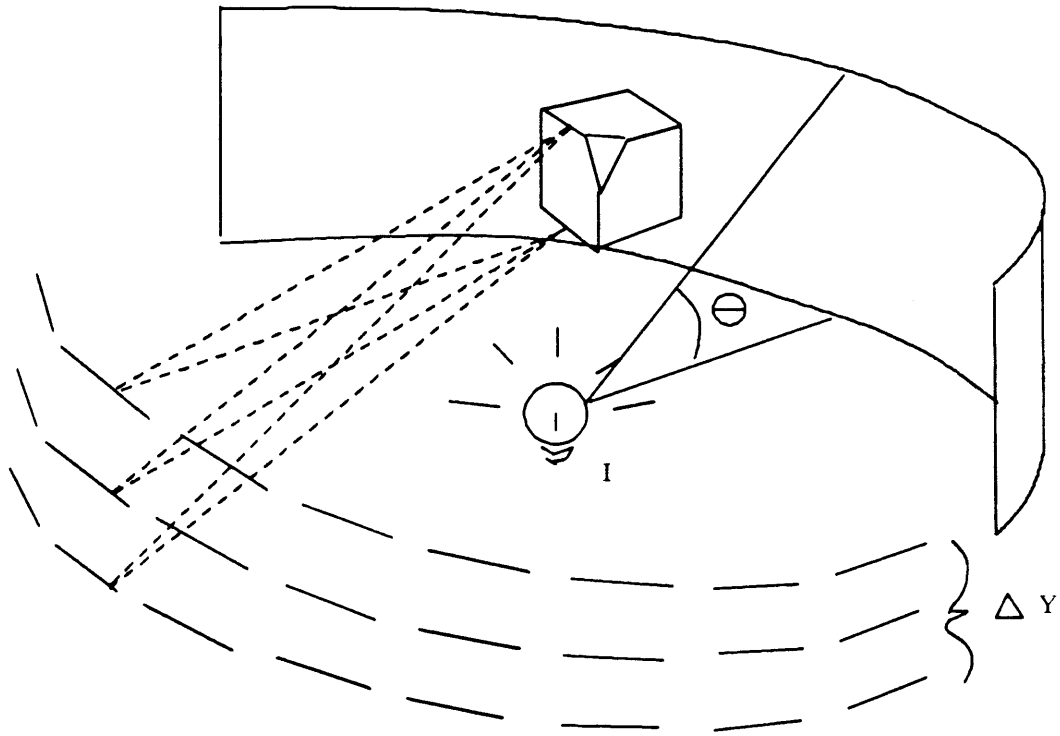


Figure 3.3: Alcove illumination geometry.

The viewing zone lies along the horizontal axis of the hologram, with an extended range Δy corresponding to the divergence of the vertical image rays (a function of the diffuser element in the imaging system).

Figure 3.4 shows the comparative viewing of both the flat and alcove formats as seen from a single eyepoint anywhere in the intended viewing area. An observer sees a series of vertical strips on the hologram surface, each presenting a different perspective of the image. These strip “sub-holograms” project a real image of the magnified transparency in-line to the original focal plane they were imaged to. Each “sub-hologram” reconstructs at a different location on the image plane (and in the case of the alcove, at a different angle) relative to the viewer. These differences result in perceived magnification changes of the image that must be compensated in order for

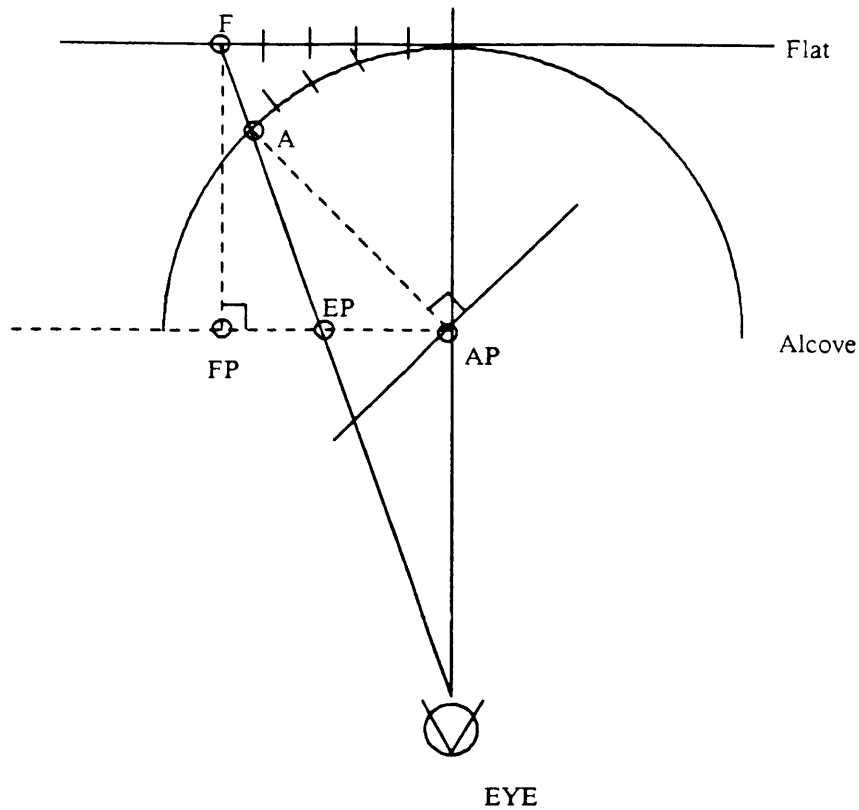


Figure 3.4: Flat and Alcove format viewing geometry.

the observed image to correctly match the perspective as seen from the viewpoint. The image must be segmented into vertical strips, and each strip presented at the proper angle and location such that they overlap in space to form a 3-D image that appears undistorted to an observer.

Hence, an eye that seems to see an image point of interest, "EP", along the horizontal span of the alcove, actually views the real image perspective reconstructed on the plane "AP" projected by element "A" at the hologram surface. In the flat format case, the observer sees "EP" actually on the plane "FP" reconstructed by element "F". In order for the images projected by the vertical strips to appear at the same angle and distance relative to the observer (and not to the planes they were originally imaged to), the images must be initially processed to account for the differences

in image screen locations and corresponding horizontal and vertical magnifications. Without prior image pre-distortion, image points of interest farther from the common projection point (namely, “AP” for the alcove format) will exhibit a greater perceptual distortion. An image rendered without distortion correction appears to bend away from the viewer.

3.1.3 Image Processing Procedure

Image distortion compensation entails complex computer processing that results in a sequence of 2-D pre-distorted views tailored for accurate (1:1) image reconstruction of the strip composited hologram. From a three-space coordinate computer graphic database, perspective viewpoints are first rendered in a geometry that is similar to the desired viewing zone of the flat or alcove hologram. This can be accomplished by ray traced graphics [22] [23] , where the distortion compensation is calculated directly, or by polygonal rendered graphics that require an additional “slice and dice” [12][11] procedure.

The anamorphic ray traced version is modelled after a pinhole camera view of the scene, wherein the pinhole is considered to consist of a pair of two crossed slits. The positions of the vertical and horizontal components can thus be located independently, and calculations made for the one ray that passes through the two slits. This technique, while quite accurate, currently requires a much greater amount of computer time to implement on a standard mainframe computer. For this reason, and because of the

availability of a sophisticated rendering package [3], both flat and alcove format images are processed using a polygon based procedure.

First, the component views (nearly 1000) are rendered in a 3-D coordinate system. Then, the views are vertically de-magnified to compensate for the anamorphic distortions of the viewing geometry, and “sliced and diced”. In this technique, the columns of any one perspective view (here 2 pixels wide) are distributed among all other perspectives and recombined as a composited “hybrid” image. Each view contains the eyepoint information of the correct perspective of the scene. The “hybrid” views are then graphically rendered on a CRT screen.

The rendered CRT images are separately exposed on 35 mm black and white film by a pin registered Mitchell camera. The adjacent perspective is then displayed, the movie frame advanced, and the sequence is repeated until all perspectives have been serially recorded. The 35mm film is processed and serves as the transparency for the holographic stereogram.

3.2 System Optics Selection

We have presented a general overview of the optical system design for producing a reflection holographic “printer”, but we now need to concentrate on our choice of optics to perform the specific functions previously described. In particular, we direct our attention toward components “B” through “E” in the imaging beam system, and components “F” through “H” in the reference beam system. This analysis will be aimed at me-

diating the trade-offs that result from alternative optics selections. The goal is to weigh these trade-offs in terms of image quality, viewing benefits, practical implementation, cost, and large scale image capability in order to formulate an optimized selection of optics for the holographic system.

3.2.1 Image Beam Optics

For the imaging system, we begin with the projector lens that functions to magnify and focus the image of the transparency to a flat field. The magnification power of the lens for a given image size can be determined by using the standard lens focusing laws. Here it is essential to invest in a high quality optic in order to reduce lens distortions, most notably barrel or pincushion distortion (resulting in non-uniform magnification of the image due to uneven curvature of the lens). A multi-element camera lens is the preferred choice.

We next select an optic whose function is to collimate the image rays at the focal plane. In this case, there are three essential possibilities, a refractive, reflective or diffractive element. For relatively small image sizes, the practical choice will be a refractive element because of efficient light utilization and in-line (axial) projection. In-line projection reduces aberrations such as coma that are exhibited by off-axis parabollic mirrors. Axial imaging is therefore desirable, providing that significant distortions are not introduced from poor quality lenses. For large image sizes, the cost and availability of large diameter collimators is prohibitive, and it may be

necessary to choose between a reflective telescope mirror or a diffractive, holographic optical element (HOE). A carefully constructed HOE will not exhibit serious lens distortions in certain reconstruction cases, but is typically not as efficient as a refractive or reflective element. Therefore, we choose to use a refractive lens as the collimating element, because of efficient light utilization, and because of the availability of a high quality convex lens for our desired image size.

The cylindrical optic functions to focus the horizontal rays of the image. Here we consider both the viewing characteristics and physical limitations for a desired image size. We recall that in the cylindrical format HPO holographic stereograms, the f-number of the lens determined the angle of view exhibited by the final hologram. Also recall that large, low f-number refractive lenses of good quality are extremely costly to manufacture. With this in mind, we consider the possibilities for our choice of lens, namely refractive or diffractive. For refractive lens choices, we can use an oil-filled plexi cylinder, a Fresnel type cylindrical element, or a lens ground from optical grade glass. However, the diffractive case is more appealing, providing the distortions and image degradation effects are not as significant as those exhibited by the Fresnel or oil-filled lenses.

We can construct a cylindrical HOE whose diffracted output produces a projected linear focus from an incident plane wave, very closely resembling the output from a plane wave incident on an ordinary refractive cylindrical lens. In the HOE case however, some percentage of the incident light will not be processed if the diffraction efficiency is less than 100 percent, and will pass through as the zero order. The zero order overlaps the diffracted

output if the HOE is constructed with a reference angle in line to the paraxial focus. For this reason, one scheme for producing the lens introduces a reference source at some angle to the H1 plane great enough to avoid on-axis interference with the linear image focus. When the H1 is reconstructed with the phase conjugate, the zero order misses the diffracted image focus completely. The off-axis recording can be made as either a reflection or transmission type hologram. A cylindrical HOE made from this method can have the low f-number characteristic we strongly desire, and accommodate a relatively large image size. This off-axis technique, however, will add an additional aspect ratio change to the image, equivalent to the angular shear of the projected on-axis image plane. Also, the image quality of the reconstructed element will be dependent on the optical quality of the components used to make the HOE.

Despite drawbacks that include aspect ratio change, the concern for impeccably clean optics used in construction (for high quality image reconstruction), and a reduction in efficient light utilization, the HOE is appealing because of cost, and good prospects for a high quality, low f-number lens. We therefore opt to construct an off-axis cylindrical holographic optical element and compensate for the aspect ratio change in the image processing stage (this construction will be described in greater detail in the following chapter).

For the diffusion element, we desire an optic that functions to focus the image rays in the vertical dimension in order to cause the image rays to diverge vertically in the reconstruction. Matters of concern here are image coarseness and dead space (which we recall from Pole is determined by

the density of the array and the location of the diffuser relative to the H1 plane). The optical quality of the element and the physical size limitations also need to be considered. Among the refractive possibilities are a linearly etched diffusion screen, or a lenticular array (cylindrical lens array). For the diffractive case, we can choose to make a holographic grating. Yet, because the diffusion element is optimally located at the H1 plane, the image will be degraded by the zero order from the grating if it is less than 100 percent diffraction efficient (we anticipate approximately 60 percent efficiency). Therefore, we choose a refractive element, namely, a lenticular sheet having high density characteristics because of efficient light utilization, elimination of zero order effects, and low cost commercial availability.

3.2.2 Reference Beam Optics

For the reference beam system, we first require a cylindrical element that functions to expand the undiverged laser beam along the horizontal dimension. The f-number is not important in this case; indeed, our main concerns are for efficient light utilization, uniform beam intensity, and a dust-free optic. Here we choose a standard refractive optic, a small cylindrical lens. Such small diameter high quality lenses are relatively inexpensive and commercially available.

We next select an optic whose function is to collimate the horizontally diverging reference beam. We can choose either a refractive lens, HOE, or mirror. Because the function of this element is to collimate unmodulated light, off-axis distortions will not be as critical as in the case of the col-

limiting element in the imaging leg. Thus, a telescope mirror is a viable choice in this instance (providing there is adequate space on the table to accommodate the focal length of the mirror). However, we use a convex lens because of availability and a limited table size for the “printer” system.

For the converging lens element, we opt to construct a spherical HOE rather than use a convex lens or mirror because the holographic procedure is a relatively simple and inexpensive one well suited for this beam-shaping purpose. The construction of the converging spherical HOE will require fewer optics than that of the cylindrical HOE, and the condition of the optics will not be as critical, because we will be able to spatially filter both the reference and object beams with a LPSF.

The construction of both the cylindrical HOE (element “D”) and spherical converging HOE (element “H”) are presented in the following chapter, as well as the optical layouts for both the flat and alcove format reflection holographic stereogram systems.

Chapter 4

Optical Construction of the Reflection Holographic System

In this chapter, we describe the optical construction of the one step reflection holographic stereogram printer, beginning with the construction of the cylindrical and spherical holographic optical elements. Both of the HOEs were made with a collimated reference beam in anticipation of plane wave reconstruction. Next, we present a schematic representation of both the flat format and alcove format “printer” systems.

4.1 Cylindrical Holographic Optical Element

The cylindrical HOE is constructed following a method proposed by Fusek and Huff [7]. In figure 4.1, we present an optical layout for producing an $f/1.0$ holographic lens for an image size 30 cm wide. With phase conjugate reconstruction, the illumination beam will diffract to form a projected focus 30 cm from the hologram plane. In order for the HOE to

maintain a constant f-number and symmetry in reconstruction, the focal line must be parallel to, and centered about the hologram plane. Thus, the subject beam optics are in-line (normal) to the H1 exposure plane. The reference beam is off-axis to the H1 exposure plane at an angle great enough to avoid contact with the subject beam optics.

The laser light is first split into the subject and reference beams by a variable polarizer / attenuator beamsplitter. The reference beam is redirected by a mirror and is focused through a pinhole and expanded by a LPSF (lens-pinhole spatial filter). The diverging beam is then collimated and strikes the hologram plane at a 45 degree angle.

The subject beam is first incident upon a quartz rod that diverges the light in the horizontal dimension. A “weak” (long focal length) cylindrical lens then diverges the beam in the vertical dimension. The “strip” of light is collimated along its length by a convex lens, then brought to a horizontal linear focus and diverged vertically by a final quartz rod. The beam is then captured at the hologram plane.

The curvature of the final quartz rod determines the angle of vertical divergence (the index of refraction is a constant 1.46). This angle, in turn, limits the f-number capabilities of the HOE lens. As the angle increases, the the H1 exposure plane can be moved closer to the linear focus and still maintain a constant area of subject beam illumination. This means that the HOE can reconstruct a linear focus closer to the hologram plane over the same vertical extent. In other words, a greater angle enables a closer focus for a given image size. Therefore, a sufficiently small diameter quartz rod will be necessary for producing a low f-number lens.

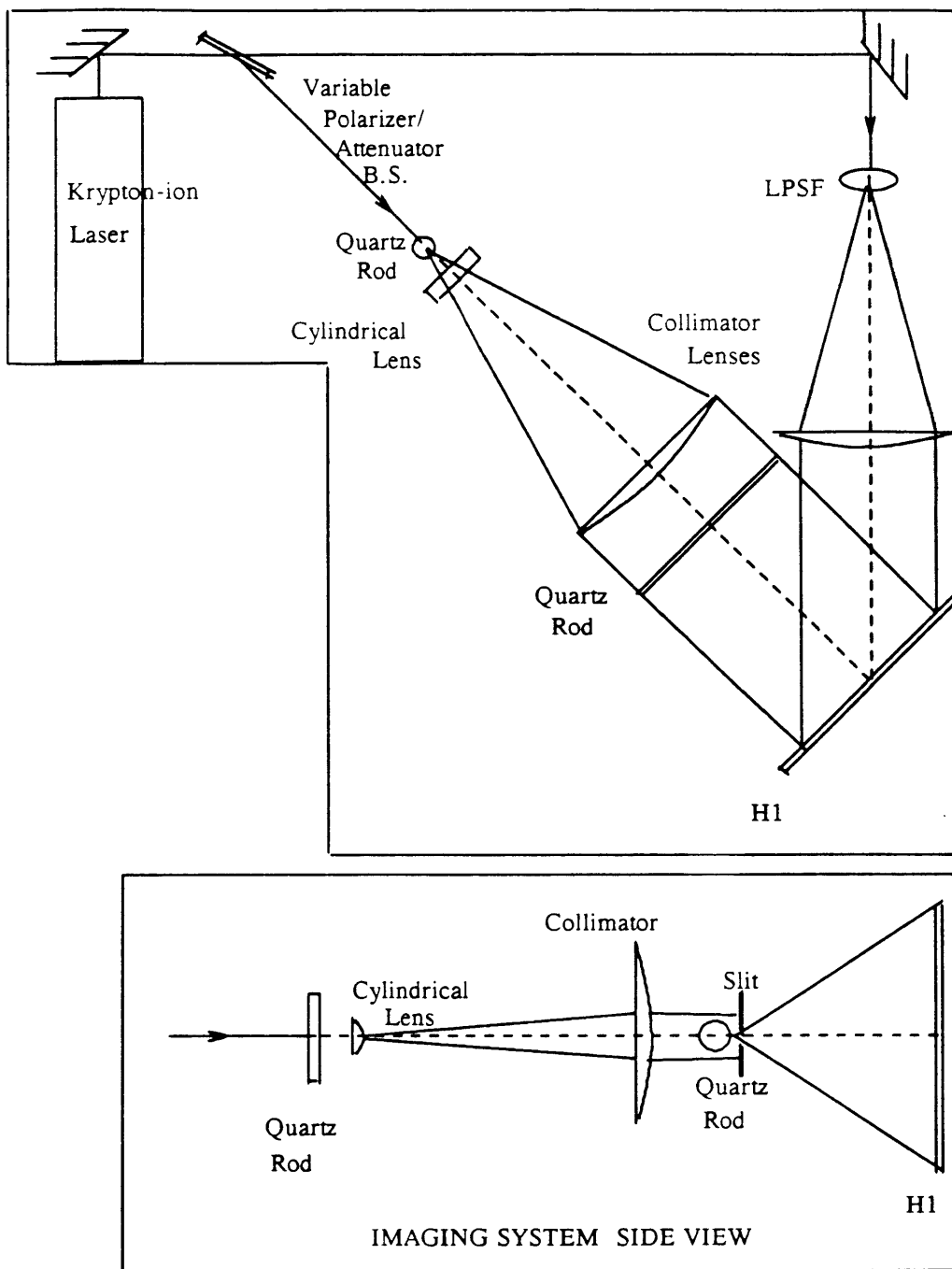


Figure 4.1: Cylindrical Holographic optical element setup.

The image quality of the HOE is critically affected by the quality and condition of the quartz rods in the subject beam path. We chose quartz over glass rods because the surface defects were fewer and less pronounced. There are several grades of quartz however, and it is important to use the highest grade rods because they are generally free from the striations and air bubbles inherent in lesser quality quartz (we used “suprasil 1” 4mm diameter quartz rods manufactured by Thermal American). Any defects in the rod will cause subject beam intensity variations over the surface of the exposure plane. These variations will result in diffraction efficiency fluctuations over different areas of the HOE. Given uniform illumination, the HOE would reconstruct a dimmer image in some areas of the hologram.

In order to produce a uniform intensity distribution of the subject beam at H1, the “weak” cylindrical lens is used to “flatten” the gaussian intensity profile of the undiverged laser beam over the diameter of the final quartz rod. In other words, we use the “weak” lens to overfill the width of the rod. Consequently, the setup requires a slit mask before the final rod to block the unfocused light from reaching the H1 exposure plane.

Because of the optical arrangement of figure 4.1, the height of the 30 cm f/1.0 HOE (and therefore of the image) is limited to the diameter of the collimator, and ultimately to the extent of the final quartz rod. It is evident from the diagram that a trade-off exists between the image height and f-number of the HOE. In this orientation, as the f-number decreases, the image height must also decrease in order to avoid obstruction by the reference beam. An alternative solution is to introduce the reference beam at a sharper angle to the H1 plane. This, however, increases the aspect ratio

distortion of the image in reconstruction by increasing the shear angle. The HOE made from this 45 degree angle allows for a 26 cm vertical extent.

When reconstructed with a collimated “time-reverse” reference wave, the HOE produced a focus approximately 0.5 mm wide, an indication of a small degree of spherical aberration. With the equivalent oil-filled or Fresnel refractive lens, this characteristic is generally more pronounced. The reconstructed image quality suffered from noticable degradation from defects in the quartz rod, but these effects were not severe.

4.2 Spherical Holographic Optical Element

Figure 4.2 is the setup used for construction of the spherical holographic lens. In this case, we interfere a plane reference wave with a diverging spherical wave. By using phase conjugate reconstruction, the illumination beam will be diffracted to form a projected point focus at the location of the original subject beam pinhole focus. For the alcove illumination geometry, we desire a point source located 25 cm away from the center of the hologram surface. Therefore, we place the subject beam pinhole focus at a greater distance from the H1 plane in order that the distance from the alcove plane, is 25 cm (see figure 4.4). Because subject and reference beams were spatially filtered, the HOE made from this diagram produced a high quality lens.

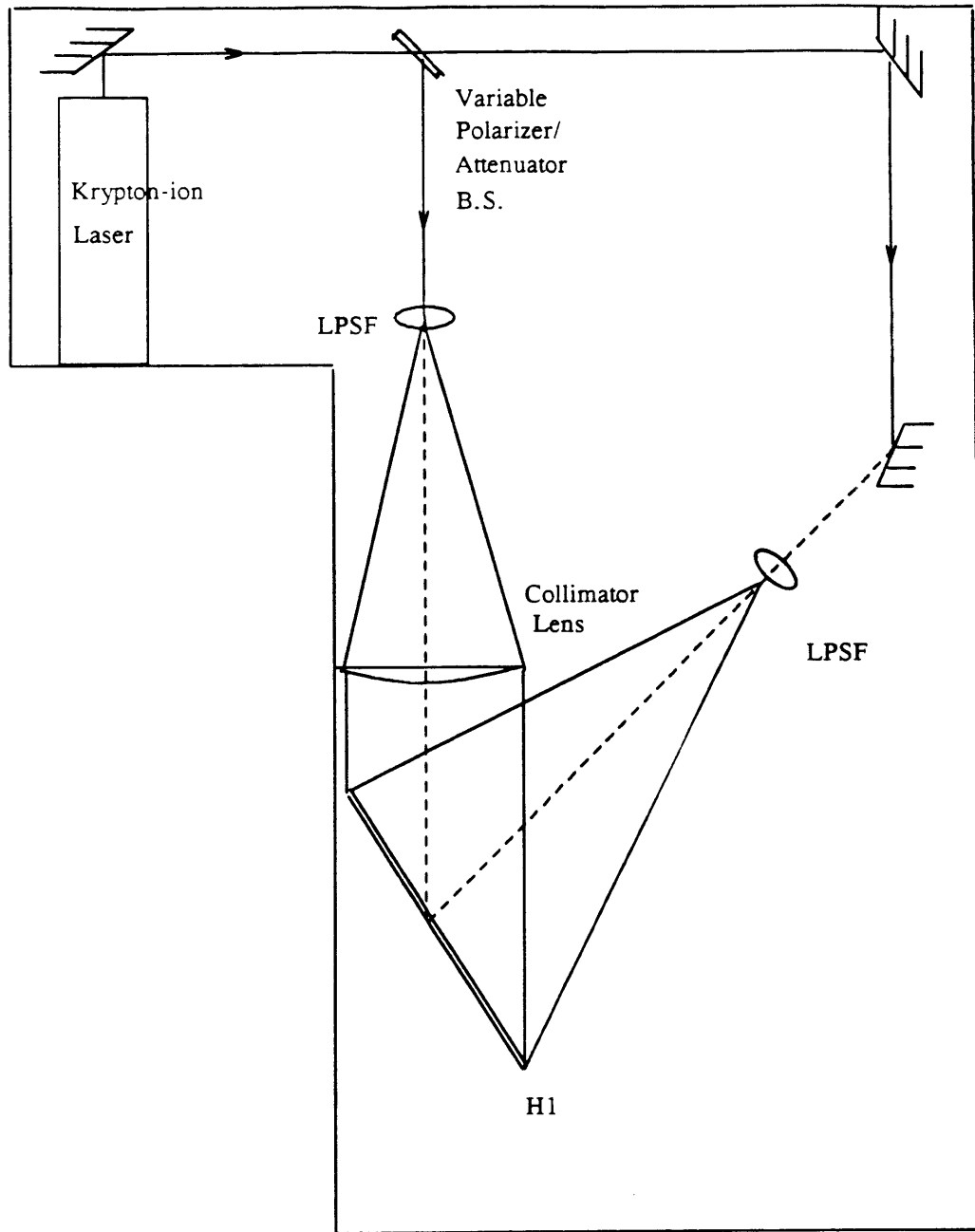


Figure 4.2: Spherical Holographic optical element setup.

4.3 The Flat Format Holographic System

Figure 4.3 represents the optical setup for the flat format holographic stereogram reflection “printer”. The description and function of the component optics “A” through “G” are the same as those given in the previous chapter (see figures 3.1 and 3.2).

4.4 The Alcove Format Holographic System

Figure 4.4 represents the optical setup for the alcove format holographic stereogram reflection “printer”. The description and function of the component optics “A” through “H” are the same as those given in the previous chapter (see figures 3.1 and 3.2).

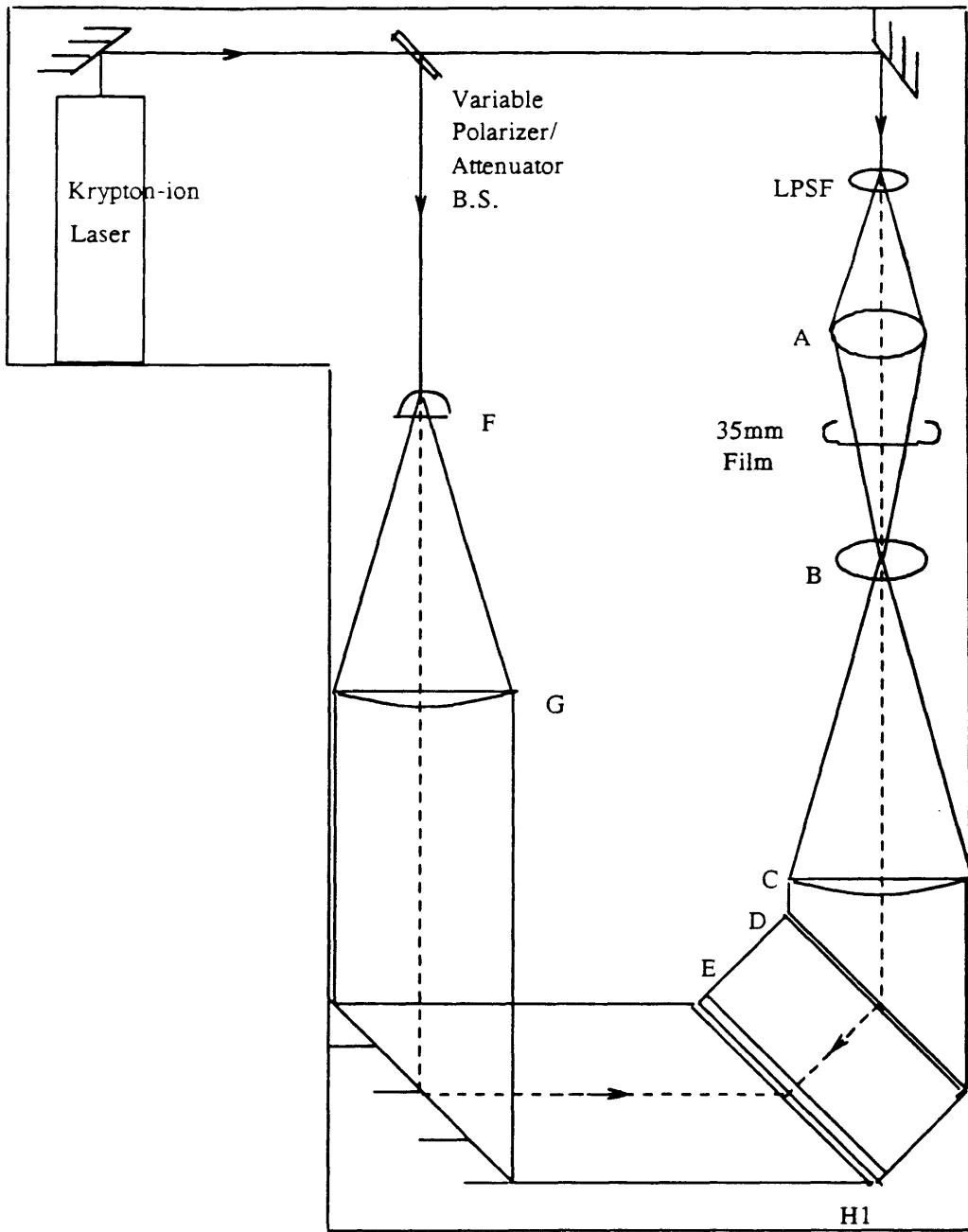


Figure 4.3: Flat format holographic setup.

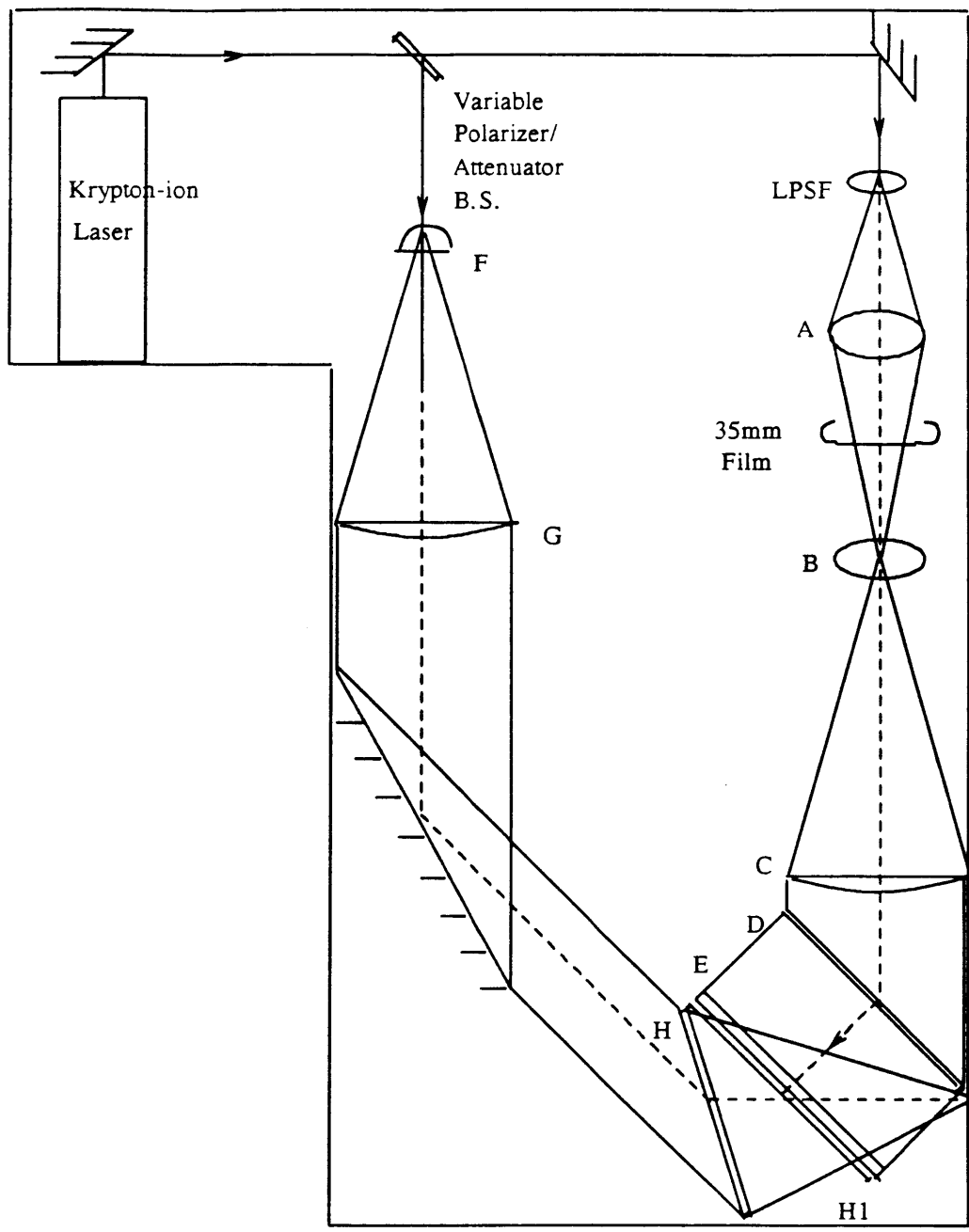


Figure 4.4: Alcove format holographic setup.

Chapter 5

Experimental Results

In this chapter, we describe the results of experimental tests conducted in both flat and alcove formats. In the primary tests, holographic exposures were made with a flat format optical setup using the appropriately pre-distorted graphics, in order to begin with a simplified recording / display geometry. Consequently, these early tests revealed a serious degradation of the image resulting from secondary reference beam interference. It turned out that the reference beam was reflected back onto the holographic emulsion by the lenticular array after initially passing through the plate from the opposite side. Modifications were then made to the optical system which effectively eliminated the problem, and high quality images were produced. Finally, tests were conducted in alcove format, with good results.

5.1 Primary Tests

The flat format exposures were made on Agfa Gaevart 8E75-HD holo-

graphic plates, using the red output (647.1 nanometers) from a krypton-ion laser. Processing chemistry is described in appendix A.

In the first exposure tests, the flat surface of the lenticular array was placed against the surface of the holographic plate and the air interface index matched with a thin film of liquid. In this orientation, the curved surfaces of the lenticular elements faced the direction of the subject beam (figure 5.1). Despite the efforts to match the index of refraction between the glass / air interface in contact with the plate, the lenticular elements reflected the incident reference rays back onto the surface of the emulsion from the opposite side of the plate. The result produced a hologram with a distinct and bright vertical linear structure in the image area. This artifact not only degraded the quality of the image, it also reduced the diffraction efficiency of the hologram for image points of interest. Consequently, the desired image reconstruction was quite dim.

In addition, the image exhibited an aspect ratio change, corresponding to a 45 degree shear of the collimated projection plane that was a result of off-axis cylindrical HOE illumination. Although this result was anticipated, it was clearly verified in the reconstruction as a vertical elongation of the image.

The reference / object intensity ratio was originally set at 1:1 for optimum brightness of the reconstructed image. This ratio, however, proved to be too low, and resulted in overmodulation effects which caused severe image degradation.

5.2 Modifications and Secondary Tests

In order to reduce the detrimental effects of the reference beam reflection, several possible solutions were posed as follows:

- 1) “flip” the orientation of the lenticular array such that the convex surfaces of the lenticular elements face away from the subject beam direction (that is, towards the emulsion).

- 2) Apply an anti-reflection (AR) coating to the lenticular surface.

- 3) Introduce an angle between the lenticular plane and hologram plane by tilting the array towards a more acute angle relative to the reference beam.

- 4) Incorporate a circularly polarized screen and AR coated glass laminate placed directly in front of the holographic emulsion, followed by the lenticular array.

Solution 1 was tried, with improved results. The linear structure was still noticeable in the reconstructed image, but only at an extreme vertical viewing angle. Still, this solution did not eliminate the reference beam reflection from contacting the hologram surface. Although it may have acted to reduce the intensity of the reflection at the emulsion, the unwanted reflection was nonetheless present, at an inclined angle. Thus, the desired image reconstruction remained dim.

Solution 2 was not implemented, owing to availability and time considerations.

Solution 3 was not tried, but the outcome is predictable, in that it must

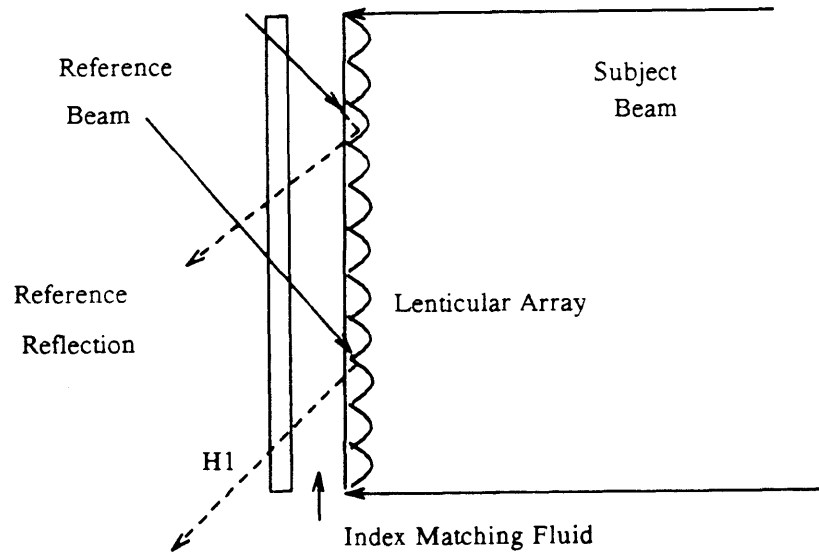


Figure 5.1: Initial lenticular orientation.

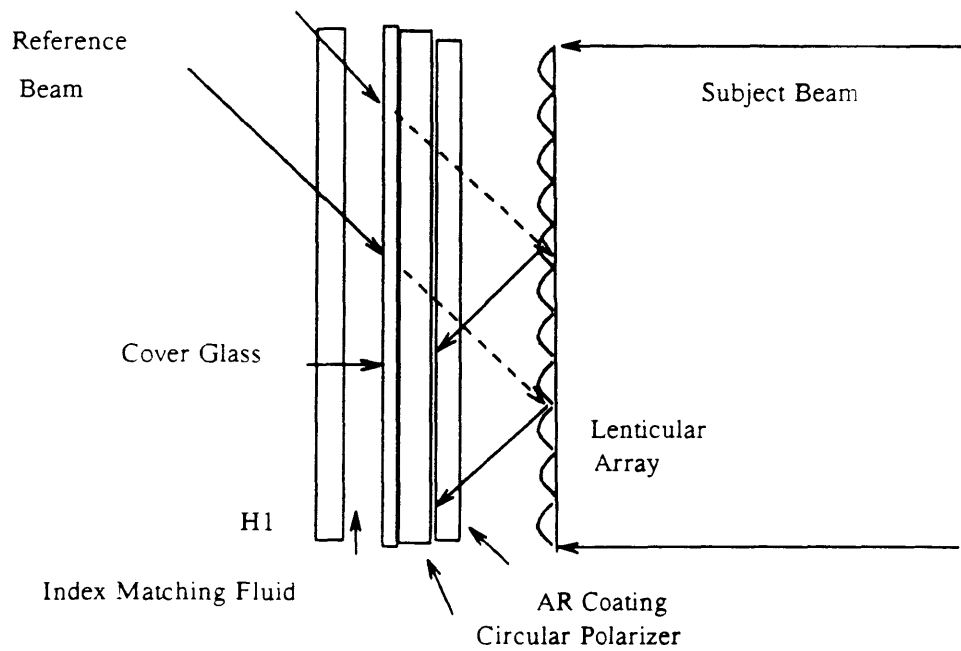


Figure 5.2: Modified lenticular orientation.

result in different vertical focus positions of the image on the H1 plane. For locations of the array very close to the H1 plane, this angle has to be quite pronounced in order for the reflection to completely miss the emulsion surface. As the lenticular screen is backed away from the H1 surface, the angle clearly can be reduced, but at a sacrifice of vertical focus.

Solution 4 was implemented, with excellent results. In order to preserve a closely matched polarization between the imaging and reference systems, and therefore obtain a brighter image reconstruction, a 1/4 wave plate was inserted in the image beam path. For best results, we integrated solution 1, and reversed the orientation of the array (Figure 5.2). Thus, the reference beam impinges on the holographic emulsion in the first pass, continues through the plate and is circularly polarized by the AR laminated polarizer. Reflections from the lenticular array are reversed in polarization, and therefore are “screened out” when they attempt to pass through the polarized sheet from the other direction.

A resolution test of the optical system was done using a USAF 1951 target transparency, imaged to infinity by repeating the 2-D frame for all viewpoints. The smallest grid can nearly be resolved by the unaided eye in white light reconstruction (figure 5.3). In this exposure we established an approximately 20:1 reference / subject intensity ratio benchmark for suitable image brightness and contrast. The aspect ratio change caused by the off-axis HOE is seen by the top feature of the image, initially a square in the target. The aspect ratio change can be easily compensated for in the computer processing stage of the graphic transparency.

Figure 5.4 is a photograph of a flat format computer graphics image,

Figure 5.3: USAF 1951 resolution target in flat format reconstruction.



Figure 5.4: "Sanji-gen" in flat format reconstruction

entitled “sanji-gen” which displays nearly 2 feet of depth when illuminated with a white light extended point source. The hologram was composited from 300 frames.

5.3 Alcove Test Results

The alcove format exposures were made on Agfa Gaevart 8E75-HD holographic film sheets, using the red output (6471 angstroms) from a krypton-ion laser. Processing chemistry is described in appendix A.

Figure 5.5 is a photograph of a “test pattern” alcove holographic reflection image, composited of 900 frames, using the appropriate image processing and optics modifications.

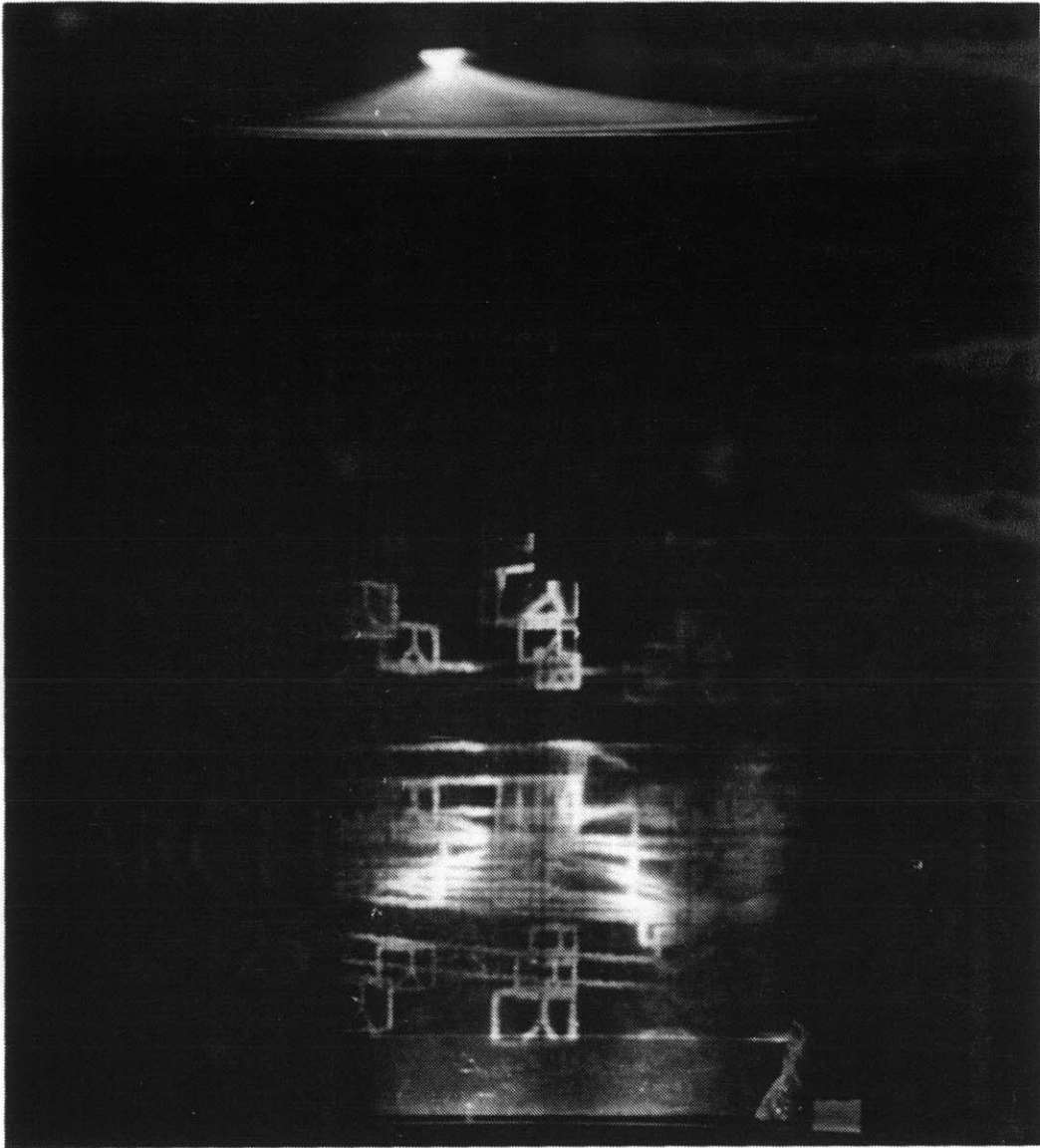


Figure 5.5: "Test pattern" in alcove format reconstruction

Chapter 6

Conclusions and Future Directions

The reflection holographic stereogram technique is a development along the lines of a fast, near “real time” computer peripheral device capable of producing 3-D hardcopy from wholly imaginary computer generated 2-D images. The procedure requires the computer graphic image to be pre-distorted in order to compensate for the anamorphic imagery evident in viewing the hologram. Unlike holographic stereograms of the past, the optical design of the reflection holographic printer eliminates the need for a second “copy” step in order to produce a 3-D real image (within the “grasp” of an observer) that can be sharply resolved with white light illumination.

The reflection holographic printer is capable of producing both flat and curved format stereograms (as a function of the computer graphic pre-distortion and illumination geometry). Yet, it is most desirable to use a format that enables the 3-D projected image to be seen by many observers at once. The alcove format is a progression along this line that enables a near 180 degree angle of view.

6.1 Image Quality Improvements

The image quality produced by the reflection holographic stereogram system can be improved in several ways. First, a spatial filtering of the quartz rods used to produce the cylindrical HOE would improve image quality by reducing the diffraction effects of lens defects and surface noise. More intricate and varied computer graphics techniques for realistic images are expanding at an enormous rate and present an opportunity for better quality images in the future. The resolution of CRT monitors is also increasing, and these offer an increase in the holographic image resolution.

6.2 Large Scale Images

An increase in the image size depends on an increase in the cylindrical HOE size while maintaining a low f-number. In one method, a non-conjugate illumination scheme can be used where the HOE is constructed and played back with a diverging wave with a sufficiently long throw distance. Another use of non-conjugate illumination would be to make the HOE in a lower wavelength than the reconstruction wavelength to reduce the f-number.

The most promising technique, however, is the stereogram multiplexed construction of the cylindrical HOE. In this method, the HOE can be built up one step at a time to any desired height.

6.3 Efficiency Predictions

The reflection holographic stereogram system can be made faster in both the computer graphics and optical systems. Specialized pre-distortion hardware will reduce the computing time necessary for processing the images once they have been rendered. There are also good prospects for a LCD light valve with high resolution that would eliminate the need for the intermediate cine camera recording of the CRT images. Thus, the images could be projected directly into the optical system. Current limitations for LCD screens are limited resolution and greyscale. These are goals for fully automating the printing step for a realization of near real time 3-D hardcopy.

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