

AD-A020 945

HOLOGRAPHIC LENS FOR PILOT'S HEAD-UP DISPLAY

A. Au, A. Graube, et al

Hughes Research Laboratories

Prepared for:

Naval Air Development Center

1 February 1976

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HOLOGRAPHIC LENS FOR PILOT'S HEAD-UP DISPLAY PHASE 3

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FEBRUARY 1976

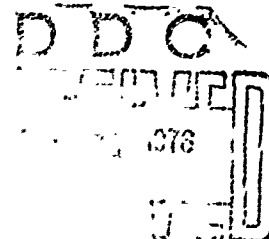
**CONTRACT N62269-75-C-0296
FINAL TECHNICAL REPORT
FOR PERIOD 18 MARCH 1975 TO 17 SEPTEMBER 1975**

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ~~N62269-75-C-0299~~ NADC-75293-30	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) HOLOGRAPHIC LENS FOR PILOT'S HEAD-UP DISPLAY-PHASE III		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 16 Mar - 17 Sept 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A. Au, A. Graube, and L. G. Cook		8. CONTRACT OR GRANT NUMBER(s) N62269-75-C-0299
9. PERFORMING ORGANIZATION NAME AND ADDRESS Hughes Research Laboratories 3011 Malibu Canyon Road Malibu, CA 90265		10. PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Development Center Warminster, PA 18974		12. DATE 1 February 1976
14. MONITORING AGENCY NAME & ADDRESS		13. NUMBER OF PAGES 107
		14. SECURITY CLASS. OF THIS REP. IF Unclassified
15. DISTRIBUTION STATEMENT Approved for Public Release. Distribution Unlimited.		16. SECURITY CLASSIFICATION DOWNGRADING
17. DISTRIBUTION STATEMENT		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Head-Up Display, Full-Scale Hologram, Dye-Sensitized Di- chromated Gelatin, Reflection Hologram Collimator/Combiner, T90-N8-21.9 Transmission Hologram		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes work on the fabrication of the full- scale holographic lens for a wide field of view (FOV) head- up display (HUD) system. The basic system parameters are a 25° FOV, a 25 in. eye relief, and a 3 in. high by 5 in. wide exit pupil. Processing equipments and techniques were fab- ricated and developed for recording the 16 in. diameter holographic element on 18 in. x 18 in. dye-sensitized		

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dichromated gelatin works include a design study of reflection hologram collimator/combiner and the fabrication and test of a T90-N8-21.9 transmission hologram lens.

The dynamically-stabilized recording apparatus for the full-scale transmission hologram lens was designed and assembled in Phase 2, Contract N62269-74-C-0642, Holographic Lens for Pilot's Head-Up Display. The construction beam optical system, based on the "continuous lens" approach, is symmetric with a 50° off-axis angle. Four plate preparation techniques were evaluated with small aperture hologram exposures. The preferred technique, adapted to large area DSDCG preparation, has good light sensitivity ($\sim 80\%$ diffraction efficiency with 300 to 400 mJ/cm² exposure) and does not need special baking and annealing processes. Fringe stability was maintained during the 2.25 hr exposure period of the full-scale DSDCG hologram lens. The optimum reconstruction geometry at 632.8 nm is 48.82° symmetric with a focal length of 14.97 in. At the center of the lens, 42% diffraction efficiency was measured with 1 to 2% scatter.

A design study of reflection hologram collimator/combiner is completed. This study was restricted to symmetric reflection holographic elements with the "continuous lens" concept on flat substrates. A baseline hologram of 43° off axis with a focal length of 14.9 in. was selected based on parametric study of field curvatures, tilts, and aberrations. Optical system design optimization resulted in a 7 element relay lens system with a folding mirror. Pupil errors were held to less than 5 mrad over a 25° FOV from a 3 in. x 5 in. racetrack exit pupil.

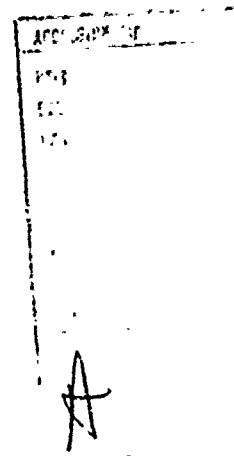
The T90-N8-21.9 in. lens is an 8 in. diameter transmission hologram lens fabricated on 8 in. x 10 in. Kodak 120-01 silver halide emulsion and bromine vapor bleached. Reconstruction geometry of the 21.9 in. focal length lens is 90° off axis, 8° asymmetric. Single binocular vision can be maintained at the eye relief distance of 34.5 in. For a nominal 63 mm separated pair of eyes centered at the exit pupil, binocular FOV is 4.16° and -3.49° vertical, $\pm 4.56^\circ$ horizontal.

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PREFACE

This final report covers the work accomplished during the period 18 March 1975 through 17 September 1975 under Contract N62269-75-C-0299, "Holographic Lens for Pilot's Head-Up Display (Phase 3)." This work was supported by the Naval Air Systems Command under the sponsorship of Mr. George Isaparas and Mr. William B. King. The program is under the technical direction of Mr. Ed Rickner, Mr. Ken Priest, and Mr. Harold Green of the Naval Air Development Center, Warminster, Pennsylvania.

The work was accomplished by the Exploratory Studies Department of the Hughes Research Laboratories, Division of the Hughes Aircraft Company, under the direction of Dr. Donald H. Close. The technical work was performed by Mr. Anson Au. Mr. Andrejs Graube optimized material characteristics and processing techniques. Mr. Cesar C. DeAnda performed many of the experiments and provided able assistance in fabricating the large aperture hologram lens. Mr. Lawrence D. Allum provided further technical support in fabricating the processing equipment. The design study of reflection HHUD systems was performed by Dr. Roger J. Withrington and Mr. Lacy G. Cook, of the Electro-Optics Department. Mr. Gaylord E. Moss acted as consultant to the program and provided valuable assistance in the conduct of all major tasks.

I. Introduction and Summary

1. INTRODUCTION

This final technical report contains detailed discussions of the Phase 3 NADC program tasks, objectives, approaches and results toward developing a Holographic Lens for Pilot's Head-Up Display.

This is the final technical report on Contract N62269-75-C-0299, Phase 3 of the Naval Air Development Center (NADC) program to develop a Holographic Lens for Pilot's Head-Up Display (HUD). The work covered by this report was performed at Hughes Research Laboratories, Malibu, California during the period 18 March 1975 to 17 September 1975.

The NADC program is to develop a HUD system meeting the optical system parameters and performance goals as stated in the NADC "Specification for Hologram Lens System."¹ The basic system parameters are a 25° field of view (FOV), an exit pupil size of 3" high by 5" wide, and an eye relief of 25 in. In Phase 1 program,² preliminary system design and recording material optimization led to a demonstration of high quality holographic HUD imaging with a half-size transmission hologram configuration with an off-axis angle of 40°. In Phase 2 program,³ we designed and fabricated a dynamically-stabilized recording system with symmetric 50° off-axis construction beams for exposing the full-scale transmission hologram.

In this Phase 3 program, the specific subject of this report, we fabricated the full-scale transmission holographic lens in dye-sensitized dichromated gelatin (DSDCG). Processing equipments were fabricated and processing techniques developed. The full-scale hologram is recorded in DSDCG derived from photographic gelatin films on 18" x 18" x 0.25" thick glass substrate. The hologram aperture is approximately 16" in diameter covering a 25° FOV from any point within a 3" x 5" exit pupil at an eye relief of 25". Table I outlines the Task, Objectives, Approach, and Results of the Phase 3 program.

The results of two other tasks are also described in this report. A design study of flat reflection hologram collimator/combiner for use in head-up display was completed. A 90° off-axis, 8° asymmetric, transmission hologram lens was fabricated in bleached silver halide emulsion. The focal length of this 8" diameter holographic element is 21.9".

TABLE 1

TASK	OBJECTIVE	APPROACH	RESULTS	LOCATION
1. Krypton laser procurement and test	Procure and test a krypton ion laser with a solution for optical coherence length and output power at 647.1 NM	Monitor power and mode stability; interferometrically measure coherence length at 647.1 NM output	Stable operation of the Spectra Physics Krypton ion laser and etalon provided 400 mW of single frequency 647.1 NM power. Coherence length was measured to greater than 1.5 meters.	Section II
2. DSDCG processing techniques development	Develop hologram processing techniques for developing DSDCG holograms recorded in photographic gelatin films on 8"x8"x1/8" thick glass substrate	Optimize processing techniques with small aperture holograms in DSDCG; adapt processing techniques to full-scale DSDCG hologram processing	Uniform DSDCG processing techniques for 16"x16" Kodak 649F plates were developed and used in fabricating the full-scale hologram	Section III
3. DSDCG laser processing equipment fabrication	Fabricate full-scale hologram processing equipment for unit to process 16" diameter DSDCG emulsion	Fabricate processing equipments, drying chamber and agitation tank as per design in Phase 2 program	Processing equipments, with minor modifications, were constructed and used as anticipated in Phase 2 program	Section IV
4. Full-scale transmission hologram fabrication and test	Fabricate and test a full-scale transmission hologram on 16"x16" plate	Fabricate the full-scale hologram in DSDCG emulsion at 647.1 NM with the dynamically stabilized recording apparatus; use processing equipment and optimized processing techniques; evaluate chief ray efficiency and scatter	Stable 2.25 hours exposure of the full-scale hologram lens was successful. Peak chief ray efficiency measured at 632.8 NM was 42% with 1-2% scatter	Section V
5. Reflection hologram collimator and scanner design study	Perform detailed design study of scanner using reflection hologram collimator; combine elements with emphasis on 25° FOV with flat hologram substrates	Parametric study of hologram configurations; computer-based optimization of a HMD optical design; evaluate pupil errors in the final system configuration	Less than 5 mrad pupil errors over a 25° FOV from a 3"x5" racetrack exit pupil was achieved in the final reflection HMD design	Section VI
6. T90-N8-21.9 transmission hologram lens fabrication and test	Fabricate and test a 90° off-axis, 8" diameter, transmission hologram lens with a focal length of 40.9"	Fabricate T90-N8-21.9 lens in silver halide emulsion (Kodak 120-01 plates) and bromine bleach; evaluate efficiency and scatter	A 8" diameter T90-N8-21.9 hologram lens was fabricated. Good display imagery was seen in a laboratory display set-up with image input at the intermediate image plane	Section VII

I. Introduction and Summary

2. SPECIFIED SYSTEM PARAMETERS AND PERFORMANCE GOALS

The optical characteristics specified by the NADC "Specification for the Hologram Lens System" are a 25° field of view, a 25 in. eye relief, a 3 in. high by 5 in. wide exit pupil, and high quality imagery.

The basic system characteristics as specified by the NADC "Specification for Hologram Lens System" are summarized in Table 2 along with the performance goals. Major parameters are a 25° circular FOV, a 25 in. eye relief, and an operating wavelength of 632.8 nm (HeNe Laser). An acousto-optical laser scanning system provides the input to the display system on a 4 in. by 4 in. diffusing screen. In order to provide a 25° FOV from this source, the system focal length must be

$$f_o = \frac{4 \text{ in.}}{2 \tan 12.5^\circ} = 9.0 \text{ in.}$$

Considering the 25 in. eye relief, 3 in. high by 5 in wide exit pupil, and the vertical tilt of the hologram element, the size of the hologram element is approximately 16 in. diameter. Only the thin film, low weight nature of hologram optical elements makes it feasible to consider such a large HUD lens size.

The "continuous lens" design approach,⁴ invented at Hughes Research Laboratories by Mr. Gaylord Moss, provides high optical efficiency across the angular FOV, and has uniform correctable aberrations. This design approach was used in providing the construction beam optical system in the dynamically-stabilized recording apparatus used to expose the full-scale lens. The full-scale transmission hologram lens, fabricated in DSDCG, provides 25° field of view display imagery at a 25 in. eye relief. The hologram focal length, f_H , is 14.97 in.

TABLE 2
25° Field of View System

Given Parameters	
Field of View	25° circular
Eye Relief	25 in.
Exit Pupil Size	3 in. high x 5 in. wide
Operating Wavelength	632.8 nm (monochromatic)
Calculated Parameters	
Hologram Size	16 in. x 16 in.
System Focal Length	9.0 in.
Hologram Focal Length	14.97 in.
Performance Goals	
Optical Efficiency	80% min
Resolution	1.0 mrad
Accuracy	1.0 mrad, central 12° 2.0 mrad, to 25°
Binocular Disparity	
Vertical	Less than 1.0 mrad
Horizontal divergent	Less than 1.0 mrad
Horizontal convergent	Less than 2.5 mrad

I. Introduction and Summary

3. SUMMARY OF FULL-SCALE HOLOGRAM DEVELOPMENT (TASKS 1, 2, 3, and 4)

The full-scale hologram was successfully recorded at 647.1 nm on dye-sensitized dichromate gelatin emulsion derived from 18 in. square Kodak 649F photographic plates.

The full-scale transmission hologram is a 48.82° off-axis, symmetric transmission hologram lens with a focal length of 14.97 in. This display geometry is the optimization of a 50° off-axis, symmetric construction geometry for 632.8 nm operating wavelength. A dynamically stabilized recording apparatus provided adequate stability during the 2.25 hours required to expose the continuous hologram lens in DSDCG.

The recording wavelength was the 647.1 nm spectral line of a Spectra Physics krypton ion laser. Single frequency power of 400 mW was obtained with a fused silica etalon. Power and mode stability was tested and improved with an insulating enclosure. Coherence length was interferometrically measured to be greater than 1.5 meters. The output power of the krypton ion laser provided approximately 280 mJ/cm^2 of exposing energy (per hour) at the center of the hologram lens.

Four holographic plate preparation techniques were evaluated based on small aperture holographic exposures made in a stable recording setup. Methylene green was chosen as the sensitizing dye due to its red light absorption in gelatin layers and exposure sensitivity. High diffraction efficiencies of greater than 80% with less than 5% scatter were achieved with two of the processing techniques requiring 300 mJ/cm^2 and 500 mJ/cm^2 exposure. Detailed description of the preparation techniques can be found in Section III, Subsection B, Topic 1.

The hologram plate preparation techniques developed with small plates were, with slight modification, successfully applied to full scale hologram fabrication on 18 in. square DSDCG plates. Dichromate concentration was lowered to .4 - .5 molar to prevent crystallization on the emulsion surface. Methylene green concentration of 7 to 10 mg/ml of dichromate was used. The sensitized DSDCG plates were dried in a humidity-controlled chamber. Following exposure, the full-scale hologram was processed in nitrogen burst agitation tanks. A twenty minutes swelling wash was followed by graduated 25%, 50%, 75%, and 100% isopropanol wash. The processed hologram is allowed to dry in a humidity-free nitrogen atmosphere. A 1/8 in. thick cover glass is sealed with Epotek 305 over the gelatin film to provide moisture and abrasion protection.

I. Introduction and Summary

4. SUMMARY OF FULL-SCALE HOLOGRAM TEST

The display geometry (48.82° off-axis, symmetric transmission) of the full-scale DSDCG hologram lens has an intermediate image tilt of 14° at 14.97 inches focal length.

The display geometry (48.82° off-axis, symmetric transmission), as well as the focal length (14.97 in.), at 632.8 nm of the full-scale DSDCG hologram lens was experimentally confirmed. Computer outputs show an intermediate image plane tilt of 14° toward being parallel with the hologram lens is necessary for aberration uncorrected imaging with the 4" square diffusing screen of the acousto-optical laser scanner. The diffusing screen is adequate to provide 25° FOV imagery to the exit pupil, 25 in. eye relief from the lens.

Peak chief ray efficiency of 42% was measured with 1-2% scatter. Linear variation between exposure and efficiency is evidenced along the vertical and horizontal dimensions of the hologram aperture. The uniformity of the construction beams can be improved by expanding the beams further at the expense of longer exposure times. Also higher efficiency would result from fine tuning the exposure energy to correspond to modifications in sensitizing solution concentrations for full-scale hologram processing.

Good display imagery was seen with the full-scale DSDCG hologram lens. Intermodulation effects of weak secondary holographic recording from reflected light off construction optics and hardware cause slight loss in resolution and contrast. The hologram aperture size (approximately 16 in. diameter) is adequate to provide 25° FOV imagery to any point within the 3 in. high by 5 in. wide exit pupil. However, due to the $12\text{ }\mu\text{m}$ thickness of Kodak 649F gelatin emulsion, low angular diffraction bandwidth causes the vignetting of some extreme field points of the 25° FOV from the edges of the exit pupil. Improved angular bandwidth can be attained with thinner films like the $6\text{ }\mu\text{m}$ 120-01 gelatin emulsion. The full field of view is visible from a large portion of the exit pupil.

The achievements in this Phase 3 program are a step forward towards developing flyable holographic head-up displays. Major points of this Phase 3 program are

- (a) Large area processing uniformity was accomplished.
- (b) Long exposure times are feasible with a dynamically stabilized recording system.

- (c) Greater than 80% diffraction efficiency has been achieved in small aperture DSDCG exposures. Similar efficiency can be obtained in large aperture exposures by fine tuning.
- (d) Thinner emulsions are needed for a wider angular bandwidth, or the FOV and/or exit pupil must be reduced.
- (e) Careful reflection shielding of construction optic and hardware is needed to eliminate secondary holograms.

I. Introduction and Summary

5. SUMMARY OF REFLECTION HOLOGRAM COLLIMATOR/COMBINER DESIGN STUDY

The final configuration of the reflection HHUD optical design meets the basic system parameters of the NADC specification and achieves less than 5 mrad pupil error over a 25° FOV from any point within 3" high by 5" wide racetrack pupil.

The final configuration of the HHUD optical design includes (a) a 43° off-axis, symmetric reflection hologram collimator/combiner with a focal length of 14.9 in., (b) a curved folding mirror to reduce the relay lens size and improve packaging, (c) a relay lens system to achieve less than 5 mrad pupil error with input imagery from the 4 in. diffusing screen of an acousto-optical laser scanner.

The major objective of the reflective HHUD optical design study is to establish the limits on the use of flat reflective holographic optical element in a head-up display. The basic system parameters, as specified by the NADC "Specification for Hologram Lens System," are a 25° circular FOV, a 3" high by 5" wide exit pupil, and a 25" eye relief. This design study was restricted to symmetric reflection holograms constructed with the continuous lens design concept.

The first phase of the study was a general parametric study of field tilts, field curvatures, and coma as a function of focal length and off-axis angle. Only hologram focal lengths between 10-16 inches were considered. Relay lens requirements outside of this range become very fast or very large in diameter. Off-axis angles were restricted to the range of 20-80 degrees. Major conclusions of this parametric study are

- (a) Focal surface tilts of off-axis holograms increase with increasing off-axis angle and are nearly independent of focal length.
- (b) Disparity in field curvatures is minimized for focal lengths of 14" to 16" and off-axis angles 40° - 60° .
- (c) Coma, the dominant aberration, is minimized for small off-axis angles and large focal lengths.

Graphical data of the parametric study are included in Section VI. Based on this study, the off-axis angle and focal length of the reflection hologram is chosen for which the relay lens system design optimization, the second phase of the study is performed.

The long focal length, 14.9 in., implies overly large relay lens. A folding mirror reduced the size of the relay elements from 7.5 to 5 inches approximate diameter and reduced the relay lens to hologram distance from 36.9 in. to 29.9 in.

The preliminary relay lens design was a derivative of a Cooke triplet. Paraxial characteristics of the system are 1.66 magnification, 5.64" focal length, and horizontal/vertical f-numbers of 1.13/1.88. The object size, input to the display system, is 4". Automatic design optimization was accomplished by the Hughes Aircraft Company in-house optical design computer program.

Pupil errors, collimation and binocular disparity, are 1 to 2 mrad over most of the 25° FOV and much of the 3" x 5" wide rectangular pupil. Computer output data of pupil errors from various pupil locations for various field points are graphically plotted in Section VI. Pupil errors are less than 5 mrad within a 3" x 5" racetrack pupil. Larger pupil errors at the corners of the rectangular pupil are believed to be a limitation of the relay lens design form.

This HUD design evolved with no specific cockpit geometry in mind. It is a one point design and must be considered as such.

I. Introduction and Summary

6. SUMMARY OF T90-N8-21.9 TRANSMISSION HOLOGRAM LENS

The T90-N8-21.9 transmission hologram, fabricated on bleached silver halide emulsion, displays laser symbology from the diffusing screen of an acousto-optical laser scanner at a 21.9 in. focal length in a 90° off-axis configuration.

The T90-N8-21.9 transmission hologram lens is a 90° off-axis, 8° asymmetric hologram lens with a focal length of 21.9". The operating wavelength is 632.8 nm. The hologram aperture is 8" in diameter recorded on Kodak 120-01 silver halide emulsion and bromine bleached. Abrasion and moisture protection is provided by sealing the hologram lens with Epotek 305 to a .25" glass substrate cut to specified dimensions. This substrate can be mounted in an AIMIS demonstrator to display laser symbology from the diffusing screen of an acousto-optical laser scanner.

Single binocular viewing can be maintained at an eye relief of 34.5 in. For eyes nominally 63 mm apart, the hologram aperture is adequate for $+4.16^\circ/-3.49^\circ$ vertical FOV and $\pm 4.56^\circ$ horizontal FOV.

Display imagery can be seen with the diffusing screen input at the intermediate image plane. This aberration-minimized plane has a 27° tilt towards being parallel to the hologram lens. Vertical and horizontal dimensions of $+1.23"/-1.13"$ and $\pm 1.75"$, respectively, are required to fill the binocular FOV. Uncorrected astigmatism across the field will cause residual aberration in the display imagery.

A peak chief ray efficiency of 11% with 8% scatter was measured at 632.8 nm. These values are similar to the half-scale demonstration hologram lens fabricated in Phase 1 program. This low efficiency is characteristic of instability in the construction system. Despite this low efficiency, the T90-N8-21.9 transmission hologram lens will adequately demonstrate the complex lens function of holographic lens and will display laser symbology in the AIMIS demonstrator. High quality display imagery was seen with a laboratory setup using diffused 632.8 nm illumination of a photographic slide at the intermediate image plane.

I. Introduction

7. REFLECTION AND TRANSMISSION HOLOGRAPHIC COLLIMATOR/COMBINER ELEMENTS

Both reflection and transmission holographic collimator/combiner elements as part of a head-up display can provide large field of view at long eye relief with high display brightness and excellent external visibility. Transmission elements are impractical in high ambient light situations, due to the presence of distracting spectral flares.

Holographic collimator/combiner elements as part of a head-up display can provide:

- (1) Large field of view at long eye relief with no increase in weight due to the thin film nature of hologram optics.
- (2) Improved display brightness and external visibility due to the wavelength dependence of optical efficiency in hologram optics.

A concise parametric analysis of reflection and transmission holographic collimator/combiner elements for head-up displays can be found in reference 2, the Phase I final technical report. The fundamental characteristics of reflection and transmission holographic elements are similar:

- (1) High optical efficiency requires point source construction beams (continuous lens design) with minimal asymmetry.
- (2) Spheroidal focal surfaces, for vertical and horizontal ray fans, have unique curvatures and tilts.
- (3) Distortions are anamorphic and keystone.
- (4) Aberrations are primarily coma with spherical aberration.
- (5) Binocular disparity and collimation errors increase with off-axis angle.

Transmission holograms typically have smaller aberrations and pupil errors than corresponding reflection holograms of similar geometry. Fabrication of transmission holographic elements, although a complex task, is less difficult than fabrication of reflection holograms. However, transmission holograms are not well suited for application in high ambient light environment. The orientation of recorded fringe structure results in strong dispersion of ambient light. The spectral flare from diffracted sunlight can be of great discomfort to the viewer. Transmission elements can be applied in controlled lighting situations where proper shielding can be achieved. Another application of transmission hologram lenses, currently being investigated at HRL, is in night vision goggles.

Reflection holograms retain the low weight and wavelength selective nature of hologram optics without objectionable spectral flare. Therefore, reflection collimator/combiner elements can provide wide FOV with high image brightness in head-up displays. However, the fabrication of reflection holographic elements requires material optimization for sensitivity and thickness uniformity, extreme control in the stability of the recording wavefront and hologram substrate, and optimization of process and sealing techniques to 'freeze' the emulsion thickness for the proper operating wavelength.

At Hughes we have the capability and experience required for a unified design of holographic and conventional optical systems. State-of-the-art fabrication techniques were developed in the successful fabrication of large aperture transmission collimator/combiner elements. Further optimization of these techniques is necessary for application to the fabrication of reflection collimator/combiner elements.

II. Krypton Ion Laser - Procurement and Test

1. SPECTRA PHYSICS MODEL 165-01 KRYPTON ION LASER

A Spectra Physics krypton ion laser with a fused silica etalon was procured to provide high, single frequency 647.1 nm output power with adequate coherence length.

The Spectra Physics Model 165-01 krypton ion laser was procured due to its high continuous power output at 647.1 nm, a spectral line near the operating wavelength 632.8 nm. The manufacturer's specifications are:

Single transverse mode power (TEM ₀₀)	500 mW at 647.1 nm
Power stability	+ .5% over 10 hrs with power stabilizer on
Input power requirement	190 to 225 V, 3-phase, 35 amps per line
Cooling water requirement	2.2 gal/min at 25 psi (minimum)

The laser cooling system is depicted in Fig. 1. The components in the system were selected to meet the cooling requirements with minimal pulsating water pressure. The regenerative turbine pump provides three gallons per minute of flow at 30 psi to the laser system.

A Model 589 single frequency, solid fused silica etalon was also procured in anticipation of the need for extended coherence length. For the 50° symmetric transmission construction geometry, the coherence length required is 22.23 cm. The theoretical spacing between adjacent optical frequencies for the model 165 laser is 143 MHz ($\Delta f = c/2L$ where c is the velocity of light and $L = 1.05$ m, the cavity length). With a Doppler gain bandwidth greater than 5,000 MHz, more than 20 frequencies can oscillate simultaneously. For a 1.05 m long laser oscillating in 20 modes, the theoretical coherence length is conservatively approximated by

$$L_H \approx .293 \left(\frac{2L}{N} \right) = .293 \frac{c}{\Delta f_0}$$

where L = cavity length, N = number of modes, c = speed of light, and f_0 = Doppler line width.

$$L_H \approx 3.08 \text{ cm for } L = 1.05 \text{ m and } N = 20.$$

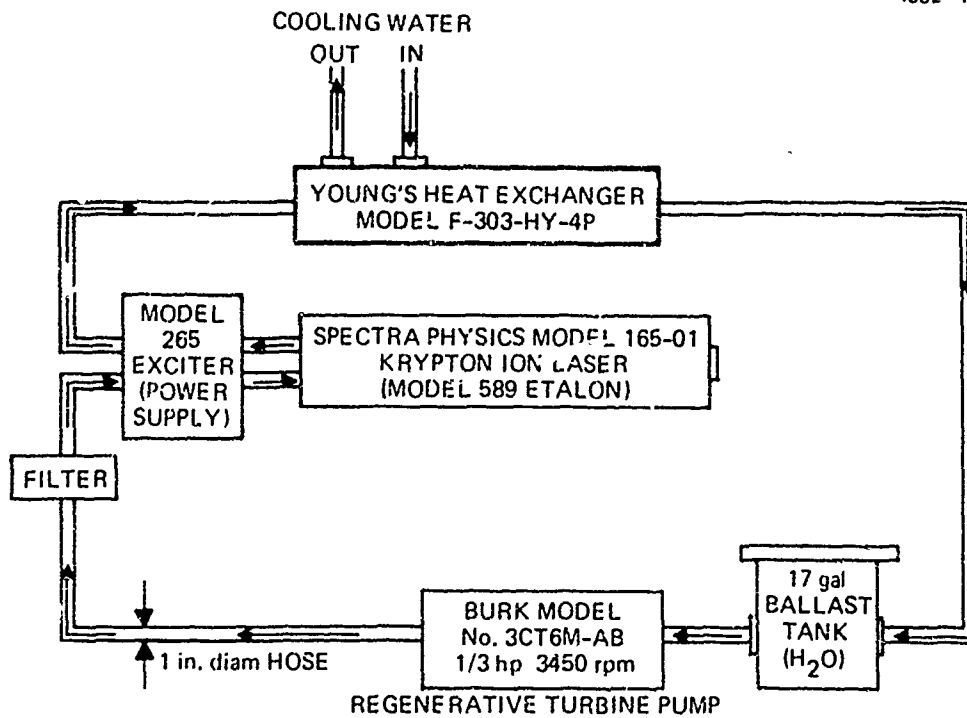


Fig. 1. The laser cooling system meets the requirement of the laser system with a 3 gal/min flow at 30 psi.

II. Krypton Ion Laser - Procurement and Test

2. LASER TEST SET-UP

The laser test setup monitors power and mode stability and interferometrically measures the coherence length of the 647.1 nm output of the krypton ion laser.

Power stability, mode stability and coherence length are evaluated by the laser test setup pictured in Fig. 2. The laser under test is the Model 165-01 Spectra Physics krypton ion laser operating at 647.1 nm. This is the laser source for the full-scale hologram recording apparatus designed and constructed in Phase 2 program.

The output of the photodiode monitors power stability on a strip chart recorder. A primary cause of power instability in the krypton ion laser is contamination of the laser optics by dust and foreign particles. Delays in this program were primarily due to this laser power stability problem. The initial laser tube was defective and cracked. The replacement tube degraded due to outgassing from some rubber and anodized components of the laser. Consequently, the laser system was returned to the manufacturer for chemical cleaning of optics and mounts. A third tube was installed, and some laser optics and an etalon were replaced.

An etalon can be considered as a filter which inhibits laser oscillation at all but one frequency or mode. The frequency or mode selected from the laser cavity modes within the laser gain profile is dependent on the optical length of the etalon cavity. Therefore a dimensional instability due to temperature variations can cause mode hops or instability. These mode instabilities can be seen visually with the spectrum analyzer. Power instability usually accompanies mode hops due to difference in laser gain of various modes.

Coherence length is measured interferometrically⁵ with the Michelson interferometer in the test setup. Coherence length, ΔL_H , is equal to $c\tau_H$ (c = speed of light; τ_H = transit time difference) such that the degree of coherence $|\mu_T(\tau)|$ is equal to $1/\sqrt{2}$. This degree of coherence is related to the fringe visibility by

$$V = \frac{2|\mu_T(\tau)|\sqrt{R} \cos \Omega}{R+1} \quad \begin{array}{l} \text{where } R = \text{beam ratio} \\ \Omega = \text{angle between} \\ \quad \text{polarization vector.} \end{array}$$

By keeping the beam ratio $R = 1$ and the polarization vector of the two beams unidirectionally parallel ($\Omega = 0$), the fringe visibility reduces to $V = |\mu_T(t)|$.

In the test setup, the fringe intensity at the detector is dependent on the intensity, relative phase difference, and degree of coherence between the two beams. By keeping the beam intensities constant with a ratio of one, the maximum and minimum fringe intensities are measured as their relative phase difference is varied by the piezoelectric translator. Fringe

visibility is calculated ($V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$) and plotted versus

ΔL . Coherence length is the ΔL at which visibility falls to .707 of maximum visibility.

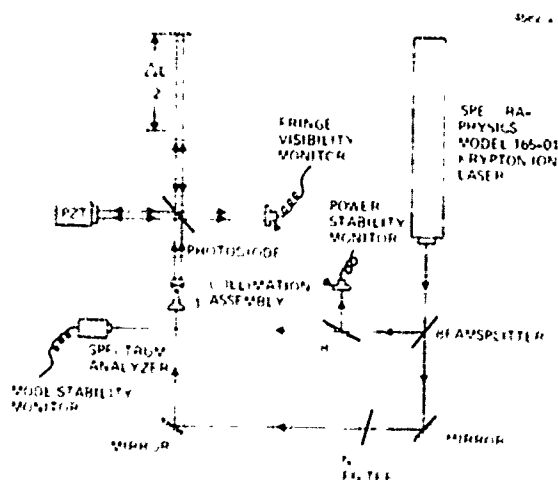
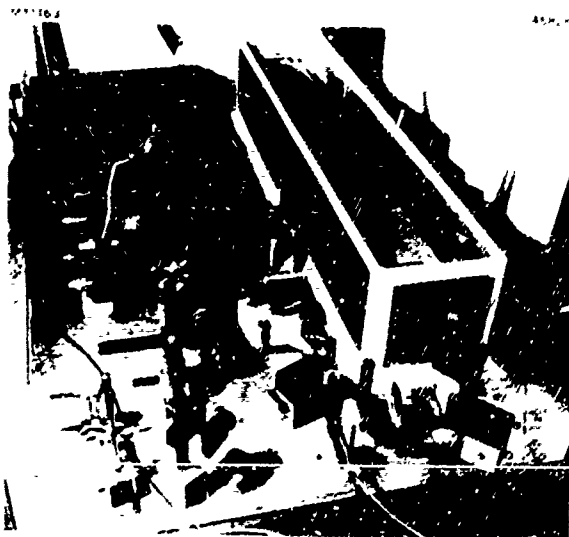


Fig. 2.
The coherence length is ΔL_H for which the fringe visibility measured is 0.707 of maximum visibility at $\Delta L = 0$.



II. Krypton Ion Laser - Procurement and Test

3. LASER TEST RESULTS

Adequate power and mode stability was achieved with 400-450 mW of single frequency 647.1 nm output power. Greater than 1.5 meter coherence length was measured.

The krypton ion laser, operating at 647.1 nm TEM₀₀ mode with one watt of power, has a coherence length of only 3.5 cm. The graph of experimental data for fringe visibility versus path length difference, Fig. 3, shows a decrease to zero visibility at 10 cm path length difference. Although high power output is available in this TEM₀₀ mode, the limited coherence length is inadequate for full-scale hologram exposures.

Single frequency operation at 647.1 nm was obtained with the Model 589 etalon in the krypton ion laser. The coherence length was experimentally measured to be greater than 1.5 meters, the limit of the test setup. Experimental data are plotted in Fig. 4. The photograph from the spectrum analyzer output shows the single longitudinal mode of the laser.

Due to the high conversion efficiency of the etalon, 600 mW of single frequency power at 647.1 nm is available with the laser system drawing 35 amps of current. However, due to the high sensitivity of the etalon to ambient air temperature, mode hops can cause the output power to vary unless the etalon is constantly readjusted to keep the optical path within the cavity constant.

An improvement in mode stability was consequently achieved by shielding the laser with insulation material and operating the laser in a light control mode. The enclosure composed of particle board is lined with aluminum foil and rubber sheet. The insulation keeps the temperature relatively constant near the operating temperature of the laser cavity. In the light control mode, the laser system compensates for power variations due to mode hops by modulating the input current to the laser. Consequently, the laser must operate below 35 amps, the saturation current level.

Optimal operating conditions for the Model 165-01 krypton laser were found to be 400-450 mW of single frequency 647.1 nm power. The laser operates at 30 amps in light control. After the temperature within the insulating enclosure has stabilized, power output was observed to be stable for over 24 hours. Mode hopping typically occurred every hour, although under extreme conditions 4 - 5 hour mode stability was achieved.

Mode and power stability will probably be much improved when a temperature controlled etalon or a more dimensional stable etalon, like the air-spaced etalon available for the 450 nm - 520 nm spectral range, is commercially available. However, the power and mode stability and coherence length of the krypton ion laser with etalon are adequate for full-scale hologram exposures. Optics in the full-scale hologram recording apparatus, designed and constructed in Phase 2 program, were aligned with this krypton ion laser.

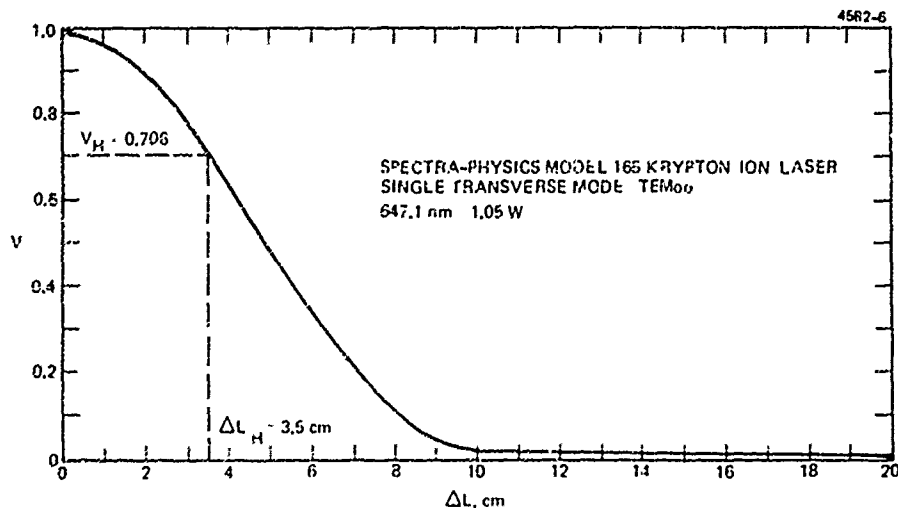


Fig. 3. Coherence length for TEM₀₀ is 3.5 cm, the path length difference at which fringe visibility is 0.707 of maximum.

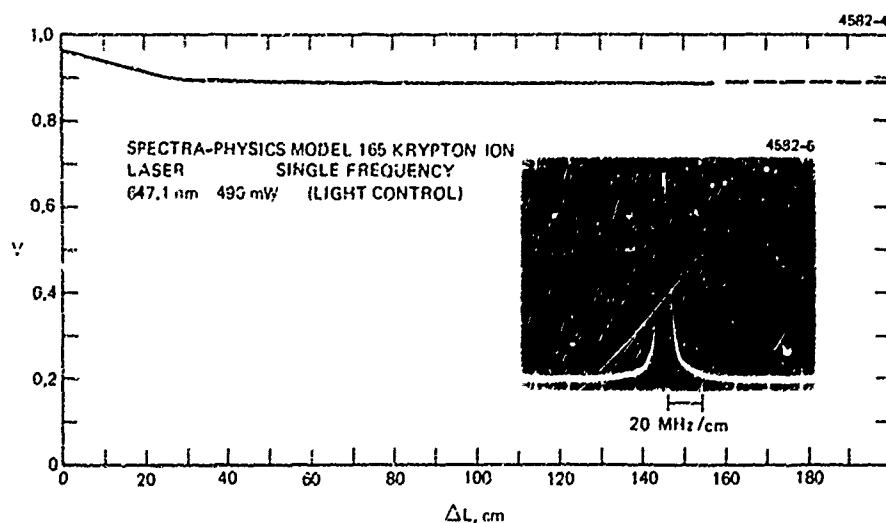


Fig. 4. Measured single frequency coherence length of greater than 1.5 m is adequate for full-scale hologram exposures.

III. DSDCG Hologram Processing Techniques Development

A. Methylene Green Dye

1. SPECTRAL SENSITIZERS

Dyes which are effective spectral sensitizers for dichromated gelatin generally show poor compatibility with dichromate ions.

The solubility of a substance is influenced by the presence of other solutes in aqueous solution. In the preparation of dye sensitized dichromated gelatin (DSDCG) sensitizing solution, a problem is encountered in providing sufficient solubility for the necessary actinic chemical species.⁶ We have found that many spectrally sensitizing dyes are capable of rendering DSDCG red sensitive, but the dyes precipitate out in dichromate solutions.

Although some dyes possess the characteristics of water solubility, red light absorption, and excellent compatibility with dichromate in solution, these dyes are typically poor spectral sensitizers for DSDCG. For example, vat green 11 (Color Index No. 69850) has a solubility product in dichromate solution exceeding 10^{-3} moles²/liter², but its quantum efficiency for index modulation production is very low. Gelatin layers sensitized with this dye have excellent red light absorption, but extremely long exposures are required to record even weak holograms.

The thiazine dyes are particularly effective DSDCG sensitizers, but their compatibility with the dichromate ion in solution is very low. The relationship between thiazine dyes and dichromate ions at the point of precipitation can be closely approximated by a solubility product relationship, typically having values of about 10^{-4} mole²/liter². Although the solubility of these dyes can be somewhat improved by the addition of a chelating agent, such as triethanolamine, or by a surfactant, such as Kodak Photoflow, the solubility is still very small. As a result, when gelatin layers are sensitized in these solutions, little red light absorption is gained, necessitating very long holographic exposures.

A more dichromate-compatible dye family is the triphenylmethane group, showing very good solubility characteristics, while maintaining fair sensitivity to red light. When these dyes are used in DSDCG, exposures of about 2000 mJ/cm² at 632.8 nm are required for efficient hologram production.⁶ Some gain in sensitivity can be gained by using a mixture of dyes. Such a mixture can contain an efficient triphenylmethane dye, for

example, acid fast violet, to increase the apparent quantum efficiency.

As a general rule, it can be stated that sensitive dyes in the DSDCG system are readily attacked by dichromate ions. Although some steps can be taken to minimize the attack, its elimination does not appear possible.

III. DSDCG Hologram Processing Techniques Development

A. Methylene Green Dye

2. SOLUBILITY IN DICHROMATE SOLUTION

The solubility of methylene green dye is determined by the amount of dye added and the concentration of dichromate present.

Although the thiazine dyes have large quantum efficiencies for converting absorbed red light into holographic index modulation, their solubility in dichromate solution is generally very low. Gelatin layers sensitized with these dyes are usually ineffective since they absorb only a small fraction of incident radiation.

The notable exception to this thiazine dye family precipitation behavior is methylene green. This dye is identical in structure to the familiar methylene blue dye, except for a nitro group in the 1-position. Apparently, this nitro group is very effective in appreciably raising the dye's solubility product, while maintaining the high level of sensitivity typically displayed by thiazine dyes. Because of these favorable characteristics, methylene green was selected as the spectral sensitizer for DSDCG.

When methylene green dye and dichromate are placed together in solution, increasing dye additions do not always produce proportionately increasing concentrations of dye in solution, as shown in Fig. 5. It would be expected that, if no other effects were taking place other than dissolution, the optical density of a dye would increase linearly with the amount of dye added until a saturated dye solution would be attained. The curvilinear plot in Fig. 5 implies that a reaction is taking place between the dye and dichromate ions.

Because of this probable dye oxidation, which is particularly rapid at large dye concentrations, the estimation of true methylene green solubility in dichromate solution is particularly difficult. However, it is possible to estimate the practical maximum dye solubility that would be present in a DSDCG sensitizing solution, namely 30.0 milligrams/cm³ of solution, or 0.082 molar. From the lower portion of this curve the real molar extinction coefficient can be estimated. It is estimated that if a 12 micron thick gelatin film expands six-fold in a sensitizing solution containing 0.082 molar methylene green, and if the gelatin does not chemically bind the dye, an optical density of 0.40 will be obtained in the dye layer. This means that an ample 60% of the active incident radiation will be absorbed in the film during a holographic exposure.

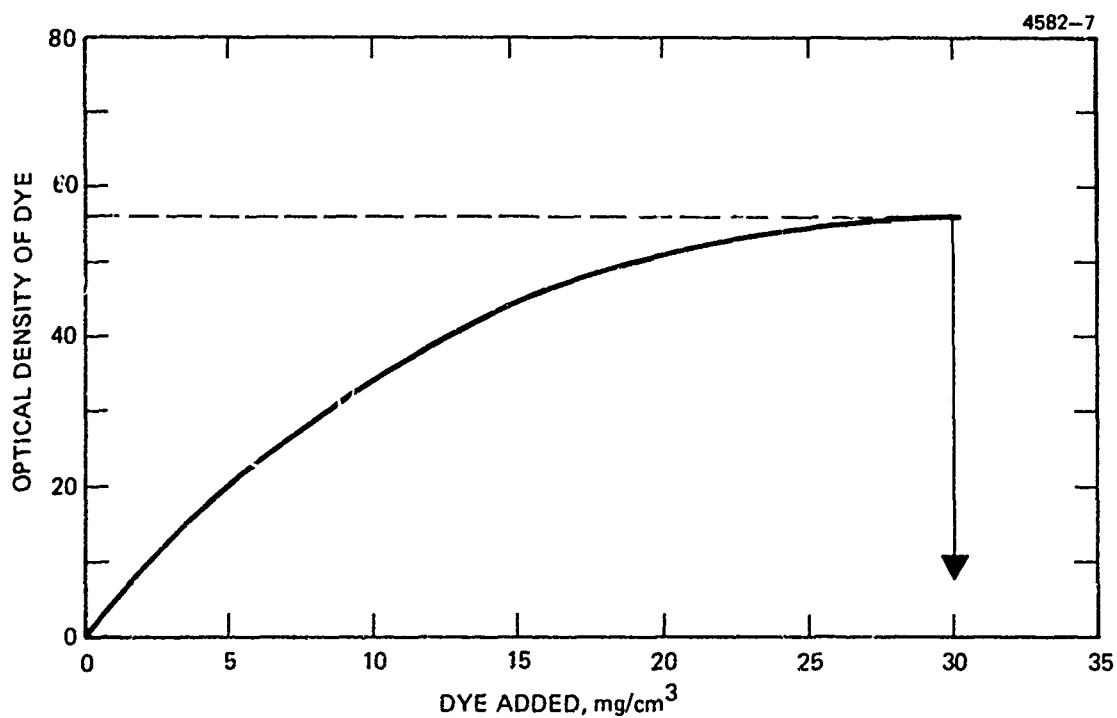


Fig. 5. Optical density developed at 632.8 nm in 1 cm path length as a function of the amount of methylene green dye added to a 1 molar ammonium dichromate solution.

III. DSDCG Hologram Processing Techniques Development

A. Methylene Green Dye

3. SENSITIZING PREPARATION SOLUTION

The sensitizing solution attains maximum optical density after two minutes of mixing and must then be filtered free of precipitate and excess dye.

Since the optical density of the dye sensitized dichromated gelatin (DSDCG) sensitizing solution does not increase linearly with the amount of methylene green dye added, as shown in Fig. 5, it is apparent that the colored dye species must be removed from solution, possibly as a result of an oxidation by the dichromate ion. This loss of optical density in the sensitizing solution is important in DSDCG in that it also influences the density that will be imbibed into the gelatin layer. We conducted an experiment to study the loss of the red light absorbancy in the preparation of the sensitizing solution and in the keeping qualities of the solution once it was prepared.

When methylene green dye is manually mixed into a dichromate solution, it has a tendency to clump together without dissolving. With additional mixing, however, the dye does begin to dissolve reluctantly, finally reaching a maximum color.

Figure 6 shows that the largest optical density is reached with two minutes of agitation. Following the maximum density, the color again becomes lighter before reaching a steady state in about eighteen minutes. The dye solution samples were filtered through medium filter paper before each density measurement to exclude any precipitate from giving a larger apparent density.

We do not have an explanation for the decrease in density from its maximum, but it appears that as the dye is being mixed into the solution, an opposing process begins to take place that removes or changes the dye molecules. It is postulated that a steady state is not reached at 52 optical density because the undissolved dye reacts with the products of the dissolved dye oxidation, forming copious precipitate. This secondary reaction, it is thought, quickly removes the oxidation products from the solution, shifting the chemical equilibrium toward increased oxidation. The practical consequence of this investigation for DSDCG is that with moderate mixing rates, optimum and maximum dye solubility is reached in about two minutes when by filtration excess, undissolved dye and accumulated precipitate should be removed.

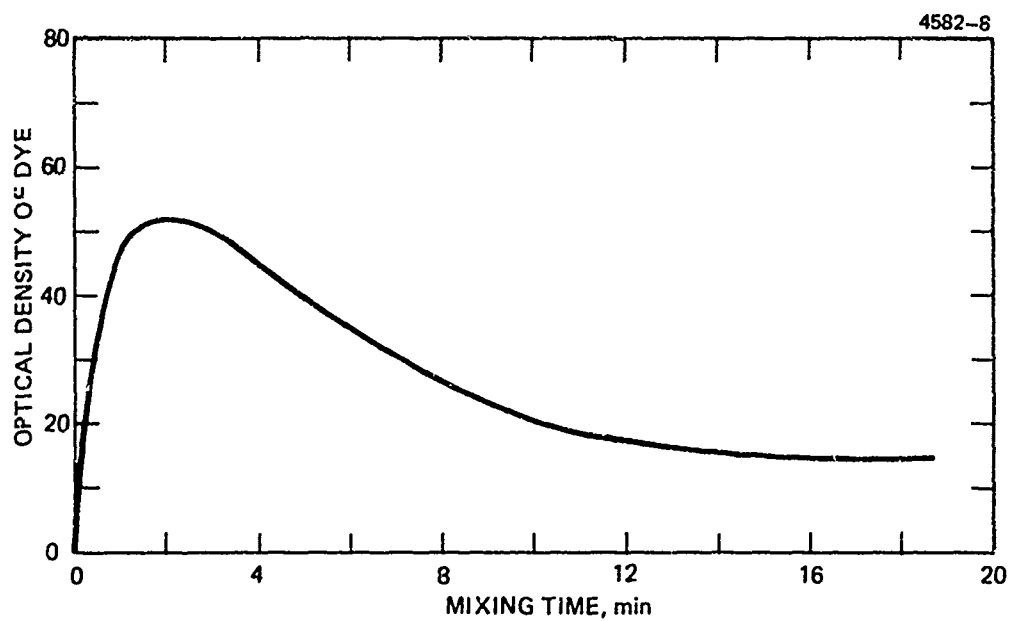


Fig. 6. Optical density developed at 632.8 nm in 1 cm path length as a function of the time of mixing of methylene green dye in 1 Molar ammonium dichromate.

III. DSDCG Hologram Processing Techniques Development

A. Methylene Green Dye

4. SENSITIZING SOLUTION LIFETIME

The filtered methylene green and dichromate solution will retain its ability to sensitize DSDCG for over sixty minutes.

In the previous section it was shown that the mixing of the dye-dichromate mixture must be properly timed to achieve optimum optical density. If filtration of the DSDCG sensitizing solution is done after two minutes, the question comes to mind as to how long the sensitizing solution will still be good. Figure 7 shows that the optical density of dissolved dye is a function of both the dye concentration and the age of the sensitizing solution. The loss of optical density with time is particularly severe at large dye concentrations, as expected, since the dye-dichromate reaction is concentration dependent. At the large dye concentrations, where DSDCG will be used, only about a 25% density decrease occurs in thirty minutes and 44% decrease in sixty minutes. We believe that the sensitizing solution could be used for at least sixty minutes, but filtration of the precipitated, oxidized dye will be necessary between sensitizations. It is anticipated that films sensitized at later times from the same solution will require somewhat longer exposure times to overcome the decreased density.

It is possible to rejuvenate or recharge the sensitizing solution after its useful time has been exceeded. Since the concentration of ammonium dichromate in the sensitizing solution is so much higher than the dye, it can be assumed that only the dye requires replenishment. Addition of new methylene green dye, agitation, and filtration produces a fresh sensitizing solution. In the production of many DSDCG holograms such sensitizing solution replenishment not only conserves the starting material chemicals, but also alleviates the problem of disposing the spent toxic materials.

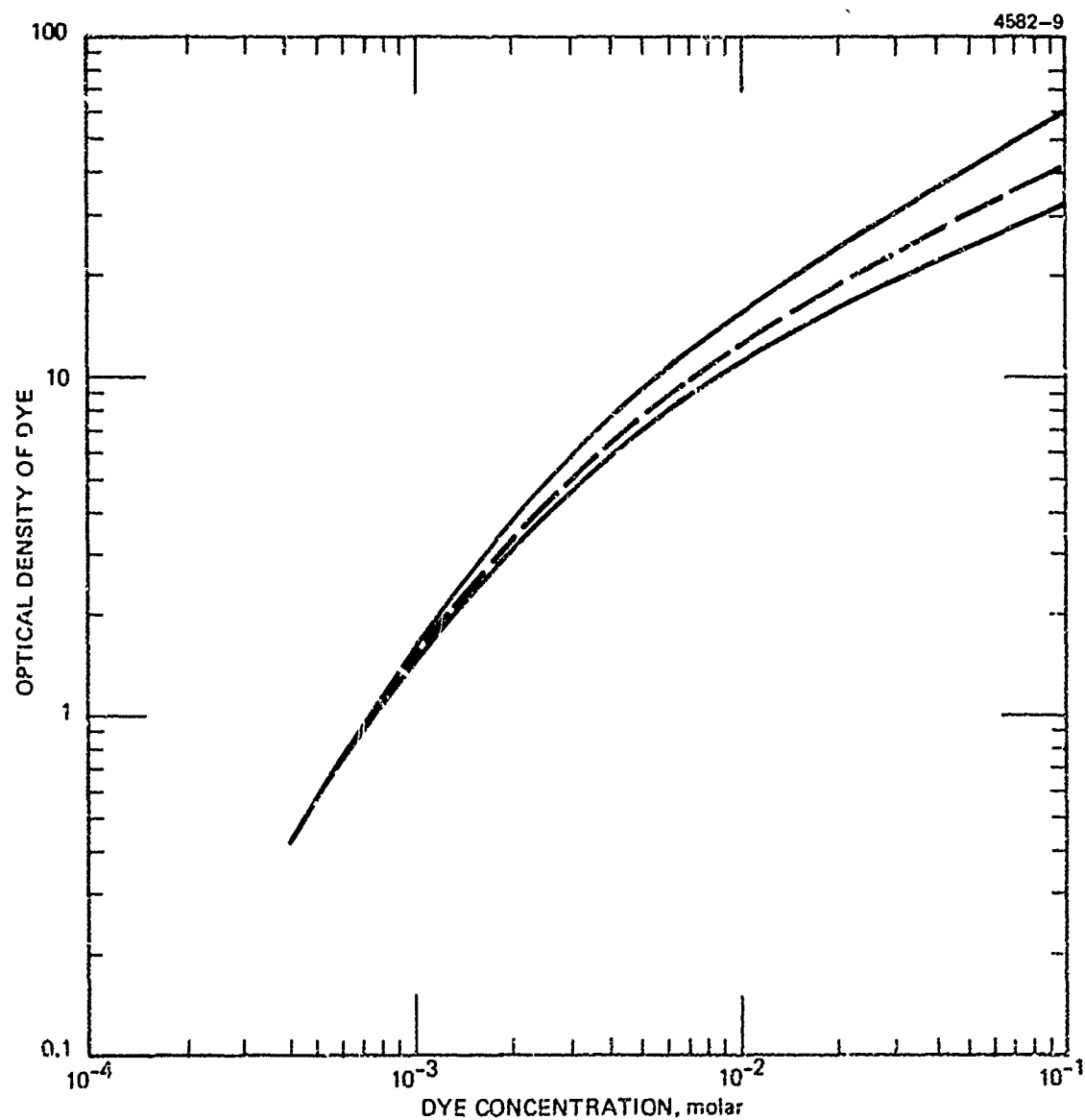


Fig. 7. Optical density developed at 632.8 nm in 1 cm path length as a function of methylene green dye concentration in 1 Molar ammonium dichromate solution immediately after mixing (—); after 30 min (- - -); after 30 more minutes (- · - · -).

III. DSDCG Hologram Processing Techniques Development

B. Small Aperture Exposure

1. PLATE PREPARATION TECHNIQUES

Four plate preparation techniques were considered for the large aperture hologram fabrication.

We extended our scope of photographic plate preparation techniques to include those which anneal or crystallize the gelatin molecules. The annealing is thought to increase the rigidity of the gelatin film⁷ and orient the molecules in positions favorable to crosslink formation,⁸ thereby increasing film sensitivity.

Besides the considerations of resulting hologram quality from each of these processes, we also considered their ease of implementation into the large hologram processing apparatus. Tables 3 and 4 show preparation methods that require annealing through the gradual rise in washing water temperature. An obvious difficulty with these schemes is in providing sufficient washing water at the proper temperature over large area holograms. Despite this disadvantage, these two techniques were further evaluated.

The technique shown in Table 5 omits the annealing cycle, but the two-stage drying in steps 3, 4 and 7, we believe, serve as a pseudo-annealing method that toughens the gelatin film. Table 6 contains the double-hardening technique, producing very hard films. This method must be coupled with special development procedures to extract maximum diffraction efficiency.²

In the next section we show holographic exposure comparison of the four dichromated gelatin preparation techniques.

Table 3

Dichromated Gelatin Preparation from Kodak
649F Plates with Annealing Cycle⁹

1. Fix in Part A of Kodak Rapid Fixer - 10 minutes.
2. Wash with running water at 90°F for 15 minutes.
Start at 70°F and raise temperature at approximately 2.5°F min. to 90°F.
3. Stand in air 1 minute.
4. Rinse in distilled water with 2 drops per liter
of Photo-Flo 600 for 30 seconds.
5. Dry completely in room environment.
6. Soak in room temperature water for 2 minutes.
7. Harden in both Part A and Part B of Rapid Fixer
for 10 minutes.
8. Wash for 15 minutes at 70°F in running water.
9. Rinse in Photo-Flo solution for 30 seconds.
10. Dry overnight at room temperature.

Table 4

Dichromated Gelatin Preparation from Kodak
649F Plates with Shortened Annealing Cycle¹⁰

1. Soak in fixer without hardener for 10 minutes.
2. Wash in running water at 90°F for 15 minutes; start at 68°F and raise temperature 2.5°F/min to 90°F; following wash, lower temperature at same rate to 68°F.
3. Soak in fixer with hardener for 10 minutes.
4. Wash in running water for 15 minutes.
5. Rinse in distilled water for 1 minute with agitation.
6. Dry overnight at room temperature.

Table 5

Dichromated Gelatin Preparation from Kodak

649F Plates Without Annealing Cycle

1. Fix in Part A of Kodak Rapid Fixer - 10 minutes.
2. Wash in tap water - 15 minutes.
3. Dry in flowing 55% RH air - 90 minutes.
4. Dry in still 40% RH air - overnight.
5. Presoak in deionized water - 2 minutes.
6. Fix in Part A and B of Kodak Rapid Fixer - 10 minutes.
7. Repeat steps 2, 3 and 4.

Table 6

Dichromated Gelatin Preparation from Kodak
649F Plates with Two Hardening Cycles²

<u>Step</u>	<u>Time</u>	<u>Temperature</u> °C
1. Apply Kodak Rapid Fixer (with hardener) mild agitation	15 min.	22
2. Deionized water wash	20 min.	22
3. Kodak Photo Flo 200 diluted with deionized water 1:200 volume ratio	30 sec.	22
4. Squeegee gelatin surface	-	-
5. Dust-free air dry, 40% RH	Overnight	22
6. Repeat steps (1) to (5)		
7. Bake in air atmosphere	2 hrs.	150
8. Store in 40% RH air		

III. DSDCG Hologram Processing Techniques Development

B. Small Aperture Exposure

2. METHYLENE GREEN SENSITIZATION

The methylene green sensitizing dye has sufficient light absorption in gelatin layers for sensitive holographic exposures.

In order to ensure good light penetration into the sensitized gelatin layer, it is necessary to keep the light-absorbing species at a sufficiently low level.¹¹ On the other hand, with too little absorption in the sensitized layer, the majority of the exposing light will be wasted. The proper adjustment of the red light-absorbing properties in dye sensitized dichromated gelatin (DSDCG) is not a simple matter since it is dependent on (1) the dissolved dye concentration in the sensitizing solution, (2) the amount of swelling of the gelatin layer, (3) the binding of the dye by the gelatin, and (4) the oxidation of the dye by dichromate after sensitization. The first variable has been studied and determined, but the last three are difficult to measure. We chose to take an empirical approach to determine the best film absorption characteristics.

After sensitization and drying, the optical density was measured in each of the plates prepared by the various processing methods. The mean optical densities for the samples were 0.807 for method of Table 3, 0.626 for Table 4, 0.862 for Table 5, and 0.808 for Table 6. It was expected that plates of Table 6 would have a lower average density since these plates had the hardest gelatin, which would swell the least. Instead, these plates had densities commensurate with much softer plates. This implies that the presensitization hardening procedures not only changed the gelatin swelling properties, but also influenced the affinity of the gelatin for methylene green.

Figure 8 shows how excessive absorbance can decrease film sensitivity. Samples were prepared by the method of Table 5 and sensitized with two different dye concentrations. The lower dye concentration plates are the more sensitive in diffraction efficiency production. The higher dye plates exhibit the "umbrella effect," where the top film layers are so dark that they shield lower layers from the image formation light.¹²

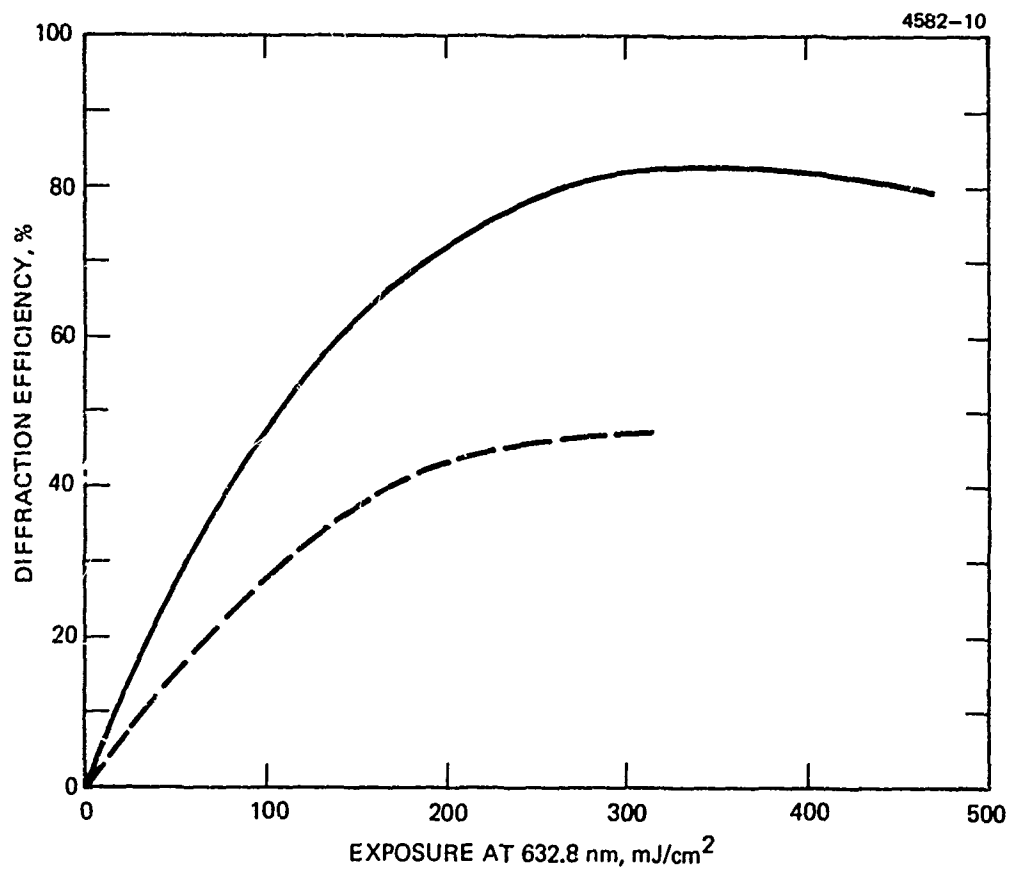


Fig. 8. Diffraction efficiency as a function of exposure energy for plates prepared with 10 mg of dye/ml (—) and 20 mg of dye/ml (----).

All of these preliminary tests were performed with a helium-neon laser at 632.8 nm, but these results, as expected, were directly applicable to the 647.1 nm wavelength also. Figure 9 shows that the red absorption spectrum of methylene green is composed of two primary electronic transitions, which may have varying efficiencies in converting light energy to crosslinks. The two wavelengths, as indicated in Fig. 9, are so close together, relative to the absorption peak separation, that no significant absorption or sensitivity differences were experimentally observed.

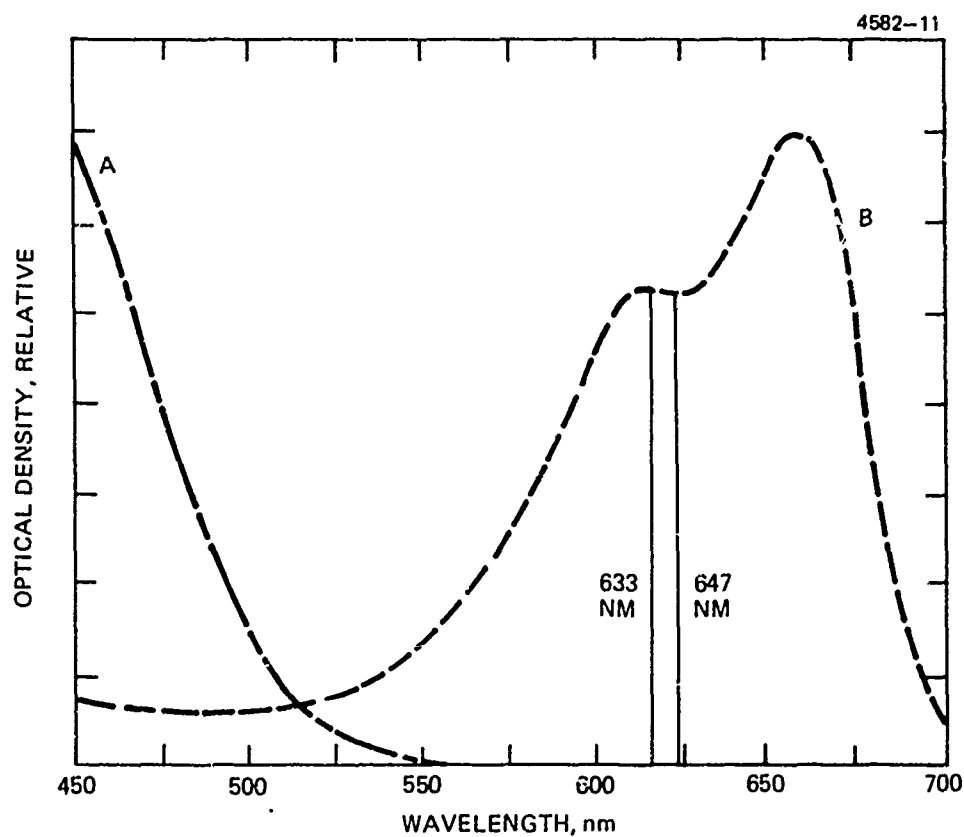


Fig. 9. Relative absorption spectra of dichromate ion (A) and methylene green dye (B).

III. DSDCG Hologram Processing Techniques Development

B. Small Aperture Exposure

3. RECORDING APPARATUS

A holographic test device with uniform illumination power and high mechanical rigidity was used for materials testing.

To determine the response of any holographic material, it is of critical importance to eliminate physical exposure variables from the exposure apparatus. The presence of optical exposing instabilities leads to the motion of holographic light fringes within the material, causing degraded material performance. Then it is very difficult to assign the relative blame for a poor hologram to the equipment or the holographic material.

In an effort to provide a very stable exposure apparatus, we used a solid aluminum plate with all the optics bolted to it as shown in Fig. 10. The laser beam entered the apparatus from the lower right side, was spatially filtered and expanded, collimated by a lens, and folded on itself by a high reflectivity dielectric mirror. The instrument was designed to provide an interference pattern with a spatial frequency so that a thick hologram would be formed in a 12 micron thick layer. The average light power distribution varied less than 10% over the exposure area.

This apparatus provided an extremely dimensionally stable holographic materials test fixture as shown by an evaluation with a Michelson interferometer. We inserted a mirror in the sample holder and made it one leg of the interferometer. After thirty minutes, the plate had not moved even a fraction of a fringe, evidencing the stability of the plate holder and supporting structure.

An air shield was provided around the metal base to keep air currents from deforming the wavefront and from influencing the gelatin layer's moisture content. The metal base was secured on four magnetic mounts, which rested on a 4x8 ft. steel table. The table, in turn, was supported by air-inflated vibrational isolation mounts.

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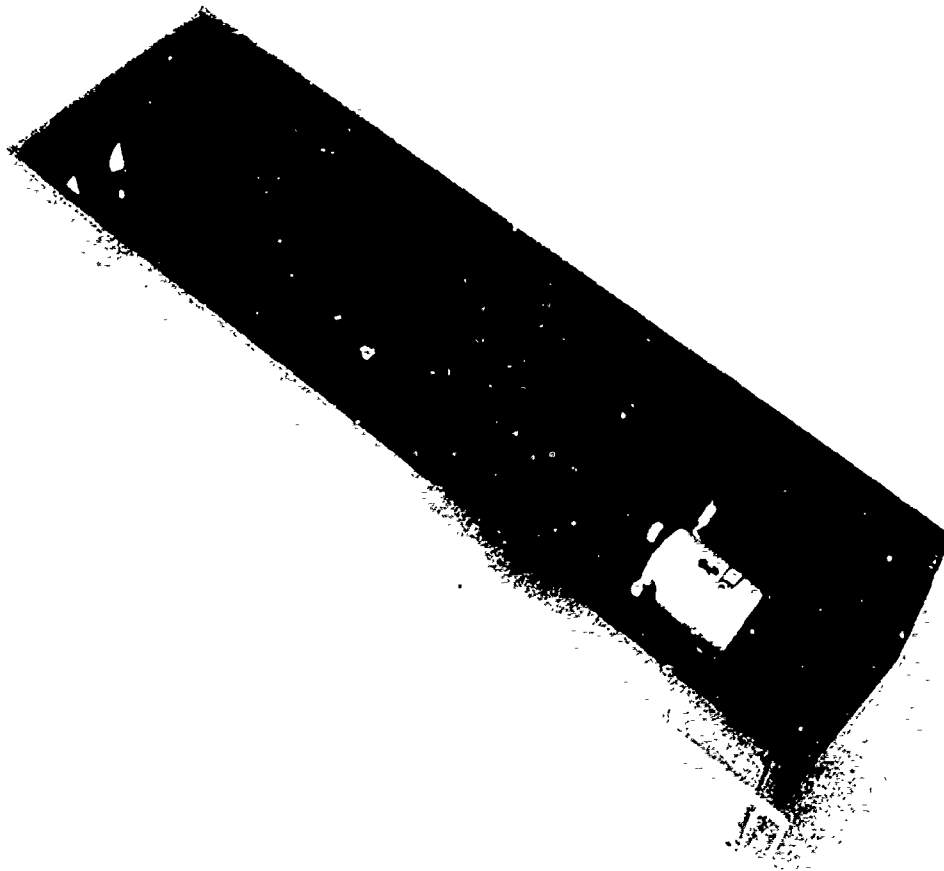


Fig. 10. Stable holographic materials test optical arrangement.

III. DSDCG Hologram Processing Techniques Development

B. Small Aperture Exposure

4. TEST RESULTS

The plate preparation techniques were evaluated by holographic exposure, and two methods showed excellent performance and were selected for large plate exposures.

In the previous section we introduced four photographic plate preparation methods as candidate techniques for the large scale holograms. We prepared several plates by each of these techniques, and following sensitization with methylene green and ammonium dichromate, we holographically exposed them in the stable apparatus shown in Fig. 10.

Following the holographic exposure, in our materials evaluation, we developed the films and interrogated them at 632.8 nm for diffraction efficiency and light losses. Figure 11 shows the results of these tests for three plate preparation techniques. The method of Table 3 at first appears to be the best, since the highest diffraction efficiency (defined as the percent of incident light diffracted into the first order) is achieved with least exposure. However, in the large photographic plates, the exposing light power distribution will not be uniform, and since the diffraction efficiency of the Table 3 method is highly peaked as a function of exposure, we anticipated the appearance of non-uniform efficiency. The efficiency non-uniformity could arise either from underexposure or over-modulation of the phase shift.

The preparative technique of Table 4 was abandoned since diffraction efficiencies only on the order of 20% could be obtained. The methods of Tables 5 and 6 were selected as worthy of further pursuit since the maximum diffraction efficiency peaks are distributed over a large exposure range. The preparative technique of Table 5 is preferred since the film is quite light sensitive, reaching maximum diffraction efficiency between 300 and 400 mJ/cm². Also, this technique does not require any special processing, such as baking or annealing, which would present special problems when applied to large scale photographic plates.

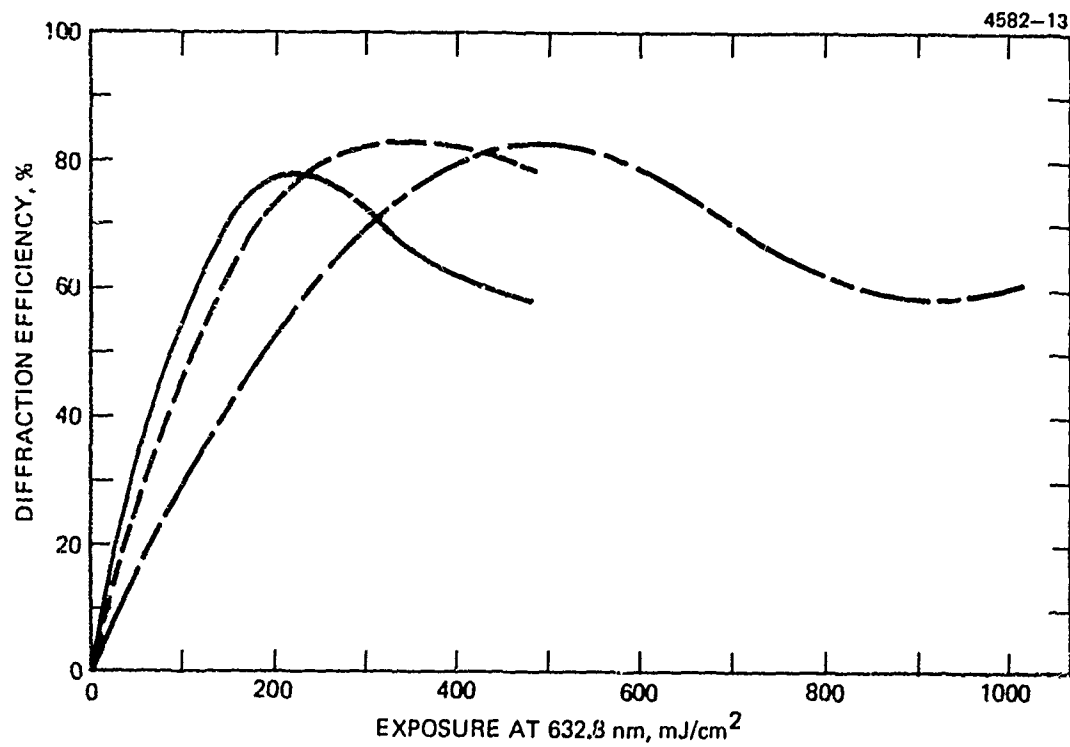


Fig. 11. Diffraction efficiency as a function of exposure for plate preparation method listed in Table 3 (—), Table 5 (-----), and Table 6 (- - - -).

IV. DSDCG Hologram Processing Equipment Fabrication

1. NITROGEN-BURST AGITATION PLATE HOLDER AND PROCESSING TANKS

The processing equipment, with minor modification, was constructed and successfully used as anticipated in Phase 2 of this program.

The preliminary design of the holographic plate processing equipment was completed in Phase 2 of this program, and with minor modifications and alterations, the equipment was constructed and utilized. In this section we shall look at the construction and testing of the processing equipment in the sequence of plate preparation.

The Type 649F plates as supplied by Kodak have silver salts imbibed into the photographic gelatin, and these salts must be removed prior to dichromate sensitization. We used flat photographic processing trays with 1200 ml of fresh Kodak Rapid Fixer for each plate. This volume of fixer is ample for removing the silver salts, and the use of fresh solution assures reproducible gelatin pre-hardening. In order to uniformly apply the fixing chemicals onto the plates, we used a two-axis pneumatic tilt table. This table generates randomly related sets of right angle waves in a shallow tray containing the plates to be processed. The small, but adequate, volume of liquid required to cover the plate is an advantage in minimizing waste chemicals when the tray is used to add a chemical solution to the plate, or when it is desired to control the temperatures of the fluid.

Washing of the fixing chemicals was done with deionized water in ten gallon tanks, shown standing on the floor in Fig. 12. The stirring was provided by nitrogen-burst agitation built into the plate holder, shown being held by the technician in Fig. 12. Originally we had planned to build a nitrogen-burst agitator in each processing tank, but we found that the holder-agitator combination could be handled and positioned much more quickly than separate holder and agitator fixtures. The nitrogen burst was provided by a valve actuated by a cam, which gave a sudden "ON" burst, lasting about three seconds, followed by about three seconds without flow. Tests showed that for washing out chemicals absorbed in large plate emulsions, this agitation method was very efficient and reproducible.

Plate baking was done in an electrically-heated oven, having six inches of refractory insulation around it to prevent temperature non-uniformities from developing. The oven was provided with a temperature sensing circuit that could hold the temperature to within 2°C of the set value.

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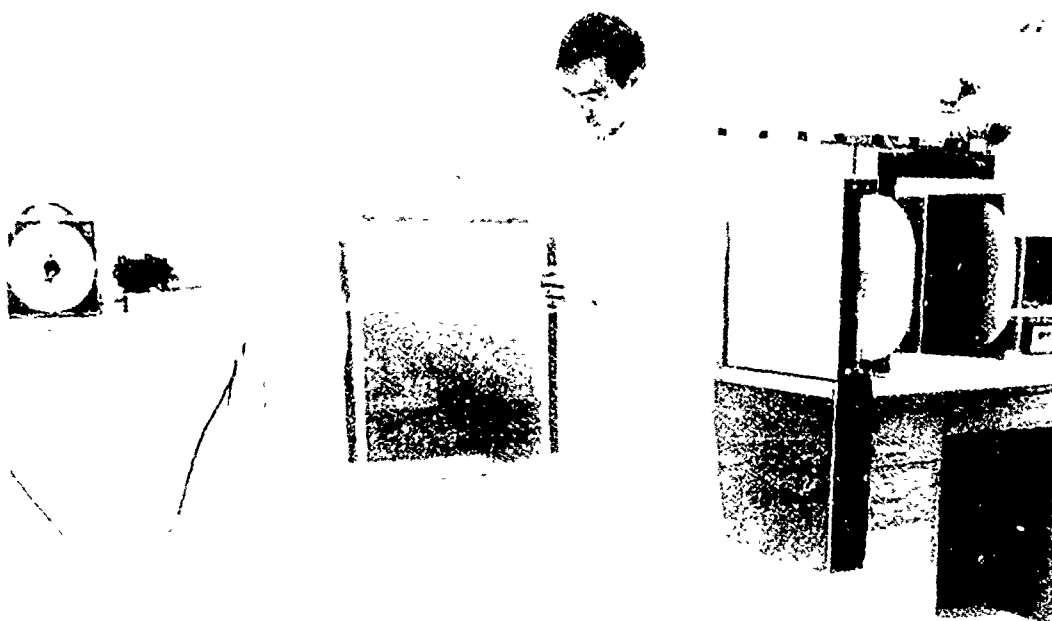


Fig. 12. Chemical processing tanks, agitator/holder, and storage boxes for DSDCG large scale holographic plates.

IV. DSDCG Hologram Processing Equipment Fabrication

2. HUMIDITY CONTROLLED DRYING CHAMBER

The processing equipment was designed and constructed to provide film uniformity and reproducibility in the post-sensitization drying and development.

Although the plate drying following silver salt removal and washing was accomplished by drying the plates in a laminar flow clean bench with 55% relative humidity air, the drying stage following plate sensitization was done in the fixture shown in Fig. 13. A 24-inch diameter fan directed air through a fibrous filter before passing over the plates at about a 45° angle to the plate surface.

The surface of the plates, when wet, is very tacky and quickly picks up dust particles from the air. The fibrous filter served as a dust shield for the plate drying area. The wet air was dehydrated by passing it over open trays of constant humidity chemical, calcium chloride ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), placed on a shelf above the fan and plates. The dried air was then recirculated again through the blowing fan.

This entire assembly was enclosed in a light-tight, plywood container, provided with temperature and humidity sensors for the inside air that could be read from the outside. When the wet plates were dried, the relative humidity would rise to about 65% in the 3 cubic meter volume enclosure before slowly falling to 40% relative humidity. We found that it was best to operate the circulating fan intermittently in order to keep the temperature inside the chamber from rising excessively.

During the drying of the sensitized plate, we noticed that the humidity in the drying chamber was significantly different from that in the room environment where the exposure was to take place. To offset the relative humidity "shock" that the sensitized gelatin plate would experience, we arranged a forced air flow over the plate during the settling time in the plate holder prior to exposure. In this way the response of the gelatin film was made more uniform over the large plate area because the relative humidity influences film moisture content, and it, in turn, influences film sensitivity.

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Fig. 13. Recirculating air, light-tight, constant relative humidity drying chamber for large-scale holographic plates.

- V. Full-Scale DSDCG Hologram Fabrication and Test
- A. Full-Scale DSDCG Hologram Processing
- 1. PRE-EXPOSURE PROCESSING

The hologram preparation techniques developed for small plates were, with some modification, successfully applied to the full scale holograms.

When photographic plates are coated for commercial sale, the manufacturer is basically interested in only that the plates perform photographically, giving proper density upon light exposure and development. The hardness of the gelatin on the plates is a minor concern to the manufacturer, and his only concern is that the gelatin does not dissolve from the plate during photographic development. Since the hardening of gelatin in photographic plate manufacture involves trade secrets,¹³ we were not able to determine how gelatin hardness is held in tolerance and had to rely on empirical observations.

Our original tests on the hardness of Kodak photographic plate gelatin were carried out on 2 x 2 inch plates by sensitizing them by increasingly stronger dichromate concentrations until the films would crystallize. For the plate preparation methods of Table 5 and 6, these dichromate concentrations were 0.6 and 0.9 molar, respectively. However, on the large 18 x 18 inch plates, the gelatin in the manufacturer's coating batch must have been much softer than on the small plates since sensitization with the 0.6 and 0.9 molar concentrations gave plates with severe crystallization, copious scattering noise, and low diffraction efficiency. We adjusted the dichromate concentrations to 0.4 and 0.5, respectively, to eliminate the crystallization problem. Also, the hypersensitizing salt, ammonium nitrate, was left out of the sensitizing solution to prevent crystallization.

In preparation of the sensitizing solution we found that when large amounts of methylene green dye (i.e., 10 grams) were added to the dichromate solution (i.e., 1000 ml), the dye had a tendency to clump into water-tight pockets. Very vigorous agitation had to be applied to the mixture to dissolve the dye. The precipitate formed by the dye and dichromate during sensitizing solution was removed by filtration through medium speed filter paper. Since the precipitate has a tendency to clog the filter paper, and since the speed of filtration is an important factor, as shown in Figure 6, we accelerated the normal filtration rate by using large area filters or vacuum filtration methods.

The precipitation of oxidized methylene green dye from solution during sensitization presented a special problem. Localized, high concentration sensitizing solution pockets would be formed around the precipitate on the gelatin surface during drip-drying of the plate following sensitization. These precipitate particles, although few in number, significantly scatter the laser light during holographic exposure. We tried several materials set on handles that would act as squeegees for wiping the liquid material from the gelatin surface along with the precipitate particles. These materials included single and double-bladed soft rubber sheets, foam rubber, leather chamois, air blades, and soft plastic. Although each had its own merits, the single soft rubber sheets were the best for removing precipitate without harming the gelatin surface.

Since it is difficult to predict the optical density which sensitization will impart to a film because of the variation in gelatin hardness, we began our sensitization with a nominal 10 mg of methylene green dye per ml of sensitizing solution. Density measurements on the sensitized plates showed that the dye content can be dropped to 7 mg/ml while maintaining adequate red light absorption. The optical density that the plates had after sensitization did not appreciably deteriorate during drying at 40% RH.

With red light illumination, however, the density dropped steadily with increasing light exposure. If it can be assumed that the dye fading rate is the same as in our previous investigation for DSDCG plates, illuminated with 632.8 nm light, a total exposure of 300 mJ/cm² should produce about a 2% reduction in red light absorption. This reduction is not thought to significantly affect film sensitivity.

- V. Full-Scale DSDCG Hologram Fabrication and Test
- A. Full-Scale DCDCG Hologram Processing
- 2. POST-EXPOSURE PROCESSING

Large scale, high efficiency holograms can be recorded in dye sensitized dichromated gelatin using graded alcohol processing.

When dye sensitized dichromated gelatin plates are holographically exposed, they develop only a small amount of diffraction efficiency. This small efficiency is typically amplified in the development process by the sequential immersion of the plate in a gelatin swelling liquid and a gelatin collapsing liquid. The critical step in this process is in the transfer of the plate from the first solution to the second. Depending on the rate at which the dehydrating alcohol reaches the swollen gelatin surface, large differences in diffraction efficiency can result.

We developed the exposed gelatin plates by first washing them for 20 minutes in deionized water with nitrogen bubble burst agitation. This step effectively removed the unreacted dichromate and most of the sensitizing methylene green dye. When the plate was immersed in the alcohol bath with nitrogen burst agitation, however, the resulting diffraction efficiency was over 70% but varied considerably over the plate area. The efficiency variation was highly correlated to the paths taken by the agitating bubbles rising to the liquid surface.

To overcome this efficiency variation, a modified development procedure was applied, where the holographic plate was bathed in graded alcohol solutions. In going from the water bath to solutions containing 25%, 50%, 75%, 90%, and 100% 2-propanol by volume, the necessity for rapid agitation of the holographic plate was obviated. The gelatin layer, in taking the water-to-alcohol transition in a gradual manner does not generate as much diffraction efficiency as when suddenly shocked with 100% alcohol, and correspondingly we achieved lower diffraction efficiencies with this method. The efficiency was very uniform over the plate surface, corresponding to the holographic exposure energy. Detailed quantitative efficiency measurements will be presented in another section of this report. The graded alcohol baths were applied to the large plates in open trays, causing a large concentration of alcohol fumes to appear in the vicinity. We found that activated charcoal respirators were necessary for the personnel to prevent pulmonary alcohol intoxication.

After the holograms were developed and dried in dry nitrogen, a cover glass was sealed over the gelatin film to protect it from moisture and abrasion. For the sealant we used a clear epoxy resin, Epotek #305, with a viscosity of about 2,000 cp. The viscosity of the sealant should be low enough to allow spreading over the hologram area, but not so low viscosity that bubble entrapment is excessive. After the two part epoxy adhesive was mixed, it was degassed for bubbles under vacuum. The resin takes about 24 hours to gain a firm hardness, and it does not photodegrade easily with sunlight illumination. The holograms sealed by this method had excellent clarity and low scattering noise. The diffraction efficiency was not significantly changed from the unsealed to the sealed state, indicating that surface relief on the gelatin surface was small in comparison to red light wavelength and the holographic lens was recorded as a volume, phase image without substantial cracks in the gelatin surface.

V. Full-Scale DSDCG Hologram Fabrication and Test

B. Full-Scale DSDCG Hologram Exposure

1. PARAMETERS

The dynamically stabilized exposure apparatus maintained fringe stability during the 2.25 hours required to expose the full scale hologram lens on DSDCG.

The fringe control system, developed in Phase 2 program, servo-locked the axial phase difference between the exposing beams. Fringe stability was maintained during the 2.25 hours required to expose the full-scale hologram. This successful long-time exposure is evidence of the stability integrity of the complete exposure system.

The krypton ion laser's single frequency 647.1 nm output, operating under light control, was 400 mW. Higher power spatial filter objectives were used to improve the illumination uniformity across the 16" hologram aperture. However, trade-offs between the degree of uniformity and length of exposure time resulted in approximately 300 mJ/cm² variation in exposed energy. The exposed energy, at various horizontal and vertical locations of the hologram aperture, is shown in Figure 14 for the 2.25 hours exposure period. Further improvements in exposure uniformity were possible but not implemented because of lack of time.

The beam ratio of the exposing beams measured 2:1. At the center of the hologram lens, the energy of the converging and diverging construction beams was .028 mW/cm² and .050 mW/cm², respectively. The calculated fringe visibility is 94% of maximum visibility of one for equal intensity beams.

After the 18" square DSDCG plate is positioned in the hologram recording plane, minor adjustment of the fringe control interferometer is required to center the low spatial frequency control fringes on the detector. This adjustment is necessary to compensate for slight perturbation of the transmitted construction beams through the glass substrate of the DSDCG emulsion. However, the adjustment requires typically less than one minute with the exposure shutter open. The absorbed energy during this period is negligible compared to the total exposure energy required.

With the exposure shutter closed, the control output of the integrator in the control electronics remains constant. Upon releasing the shutter, the control electronic integrates phase difference between the construction beams. The control

output drives a piezoelectric translator correcting any phase difference variations during the exposure.

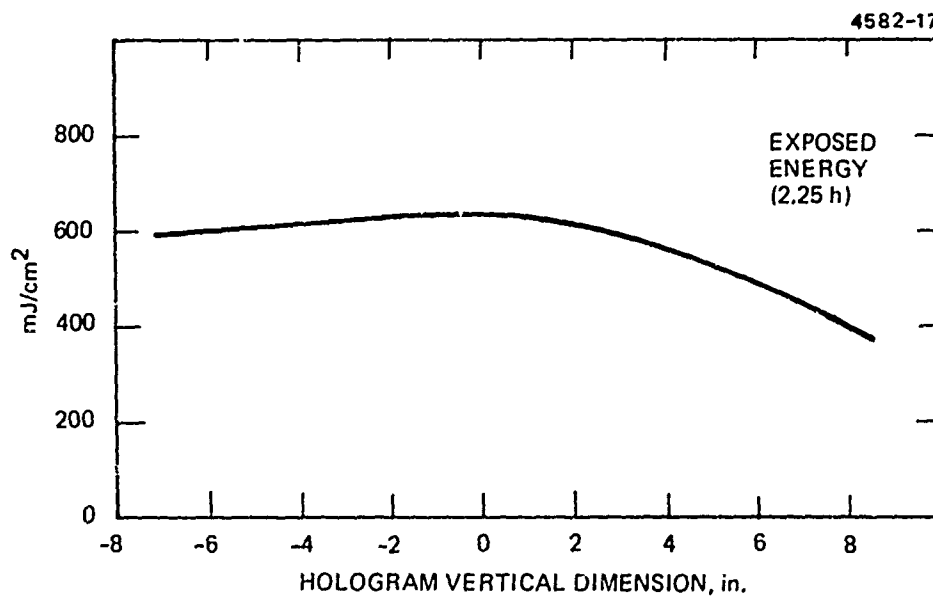
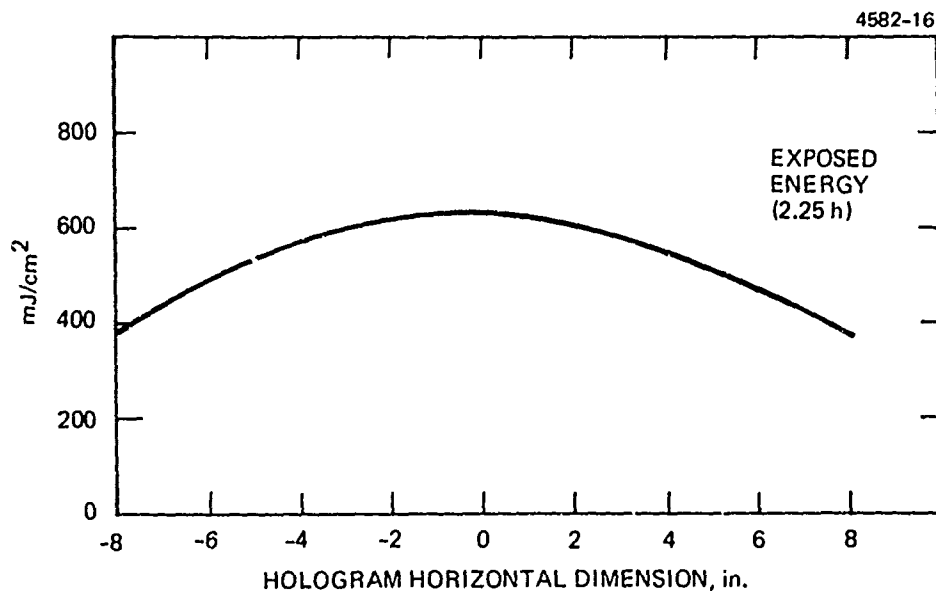


Fig. 14. Variation in exposed energy across vertical and horizontal dimensions of full-scale hologram lens.

V. Full-Scale DSDCG Hologram Fabrication and Test

C. Full-Scale Hologram Characteristics

1. DISPLAY GEOMETRY AND INTERMEDIATE IMAGE PLANE

The full-scale hologram HUD geometry at 632.8 nm is 48.82° off-axis with a 25 in. eye relief. The intermediate image plane tilt is 14° at 14.97 inches focal length.

The full-scale hologram recording apparatus was designed and fabricated for a 50° off-axis symmetric transmission construction geometry. Slight modifications to this construction geometry is required for optimal 632.8 nm wavelength reconstruction in a symmetric configuration. This is summarized in Table 7, and a vertical section of the HHUD geometry of the full-scale hologram is shown in Figure 15.

Computer ray trace data of the hologram's focal surfaces are plotted in Figure 16. The relay lens system design represents a complex task because of the disparity in object surfaces and is not within the scope of this Phase 3 program. However, an intermediate image plane can be selected to provide display imagery from the 4" square diffusing screen of the acousto-optical laser scanner.

The intermediate image plane is the bisector to the axial tangent planes of the spheroidal focal surfaces shown in Figure 16. This image plane is tilted vertically towards the hologram, 14° from the optical axis normal at the focal length of the lens, 14.97". The required input size for 25° circular FOV can be measured from the optical axis to the extreme field points on the intermediate image plane, incident points for the $\pm 12.5^\circ$ field rays.

With the 4" square diffusing screen, tilted 14° , + 3.75 in. and -3.19 in. is adequate for 25° vertical FOV. A horizontal dimension of +3.31 in. is necessary for 25° horizontal FOV. Residual aberrations will exist in the display imagery of the intermediate image plane (4" square diffusing screen), because of the absence of an aberration-correcting relay lens system.

TABLE 7

Full-Scale Transmission Hologram

Construction at 647.1 nm		Reconstruction at 632.8 nm	
Asymmetry angle	0°	(Symmetric)	0°
Off-axis angle	50°		48.82°
Focal Length	14.58 in.		14.97 in.

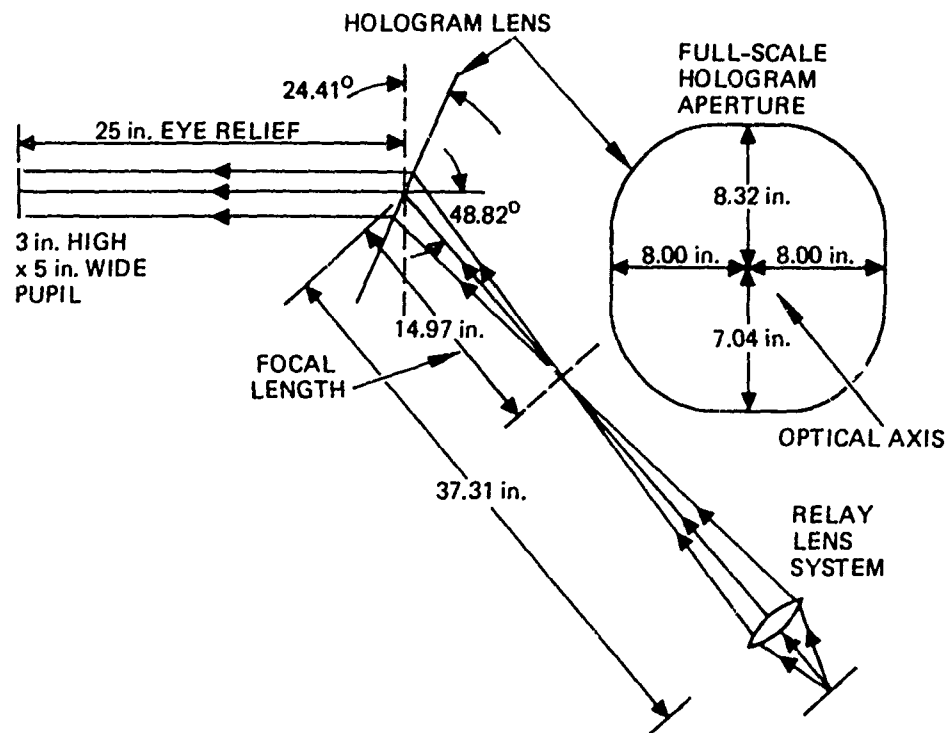


Fig. 15. Full-scale hologram HUD geometry at a display wavelength of 632.8 nm.

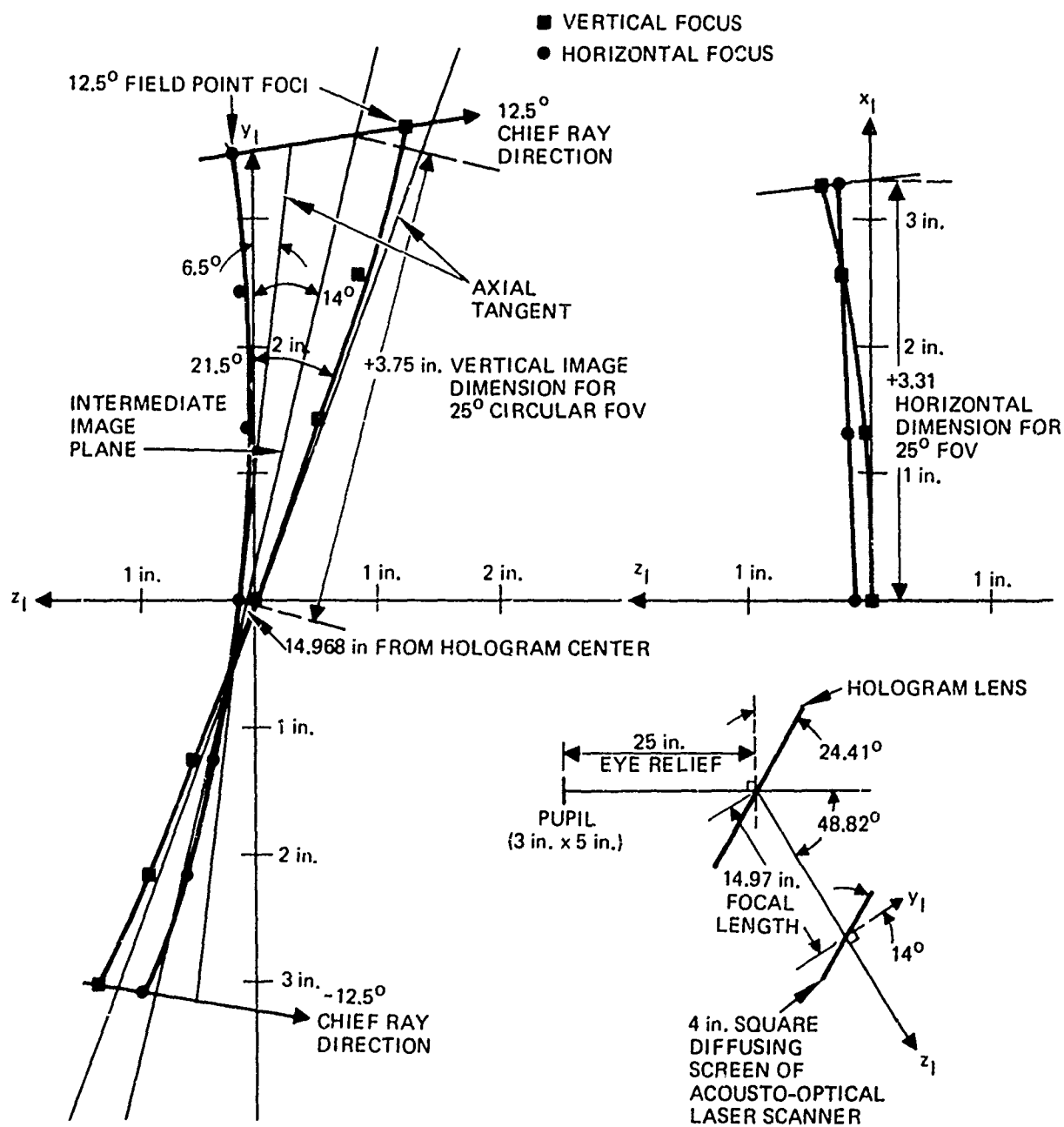


Fig. 16. Vertical and horizontal section of focal surfaces and intermediate image plane.

- V. Full-Scale DSDCG Hologram Fabrication and Test
- C. Full Scale Hologram Characteristics
- 2. EFFICIENCY AND SCATTER

The full-scale hologram display geometry at 632.8 nm was confirmed experimentally. Peak diffraction efficiency of 42% was measured with approximately 1-2% scatter.

Symmetry, off-axis angle, and focal length of the full-scale transmission hologram was experimentally measured at 632.8 nm, the operating wavelength of the laser scanner. The display geometry of the full-scale DSDCG hologram lens was confirmed to be 48.82° off-axis, symmetric transmission with a focal length of 14.97 inches. Detailed discussion of the test procedures can be found in Reference 14.

Chief ray efficiency and scatter, measured at 632.8 nm, is plotted in Figure 17. Diffraction efficiency is the percent of incident light diffracted into the first order. Scatter is the percent of incident light loss not accounted for in diffracted and transmitted light, corrected for surface reflections and film absorption. Peak efficiency of 42% was measured at the hologram optical center. With typical reflections of 6-7% and absorption (measured in unexposed regions) of 16%, the scatter of the processed DSDCG hologram is well below 5%.

Note that chief ray efficiency and scatter data was measured and plotted for field angles greater than the $\pm 12.5^\circ$ FOV. Because chief rays of the HHUD system are construction rays of the hologram lens the graph in Figure 17 also shows the diffraction efficiency variation across the 16" diameter hologram aperture. A direct correlation exists between this variation and the exposure variation (Section V, Topic B1) across the hologram aperture. Consequently, chief rays incident at points of high exposures, near the hologram optical center, had high diffraction efficiencies. Because diffraction efficiency does not appear saturated versus exposure, higher diffraction efficiency could probably be attained with increased exposure.

During a laboratory display setup of the full-scale transmission DSDCG hologram lens, ghost imaging was noticed in the display imagery. Consequently, this secondary imaging was tracked down to actual weak holograms of construction hardware and optics. These holograms were formed by reflections of the construction beams off these construction hardware and optics during the exposure. The overall

intermodulated effect of these weak holograms is to produce faint shadow-like images causing slight contrast reduction and resolution loss. These secondary holograms can be eliminated with antireflection coatings of problem optical surfaces and re-anodizing problem construction hardware.

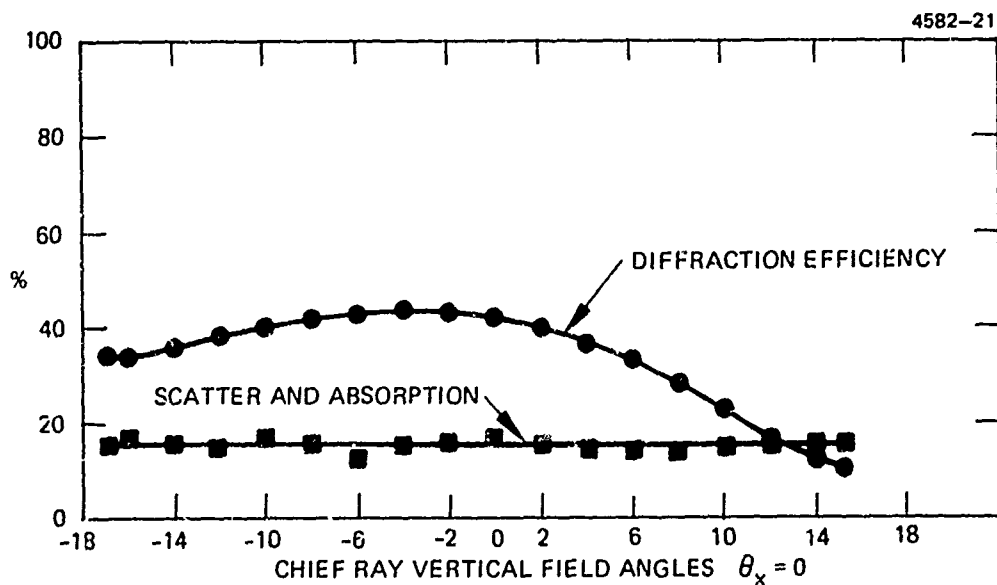
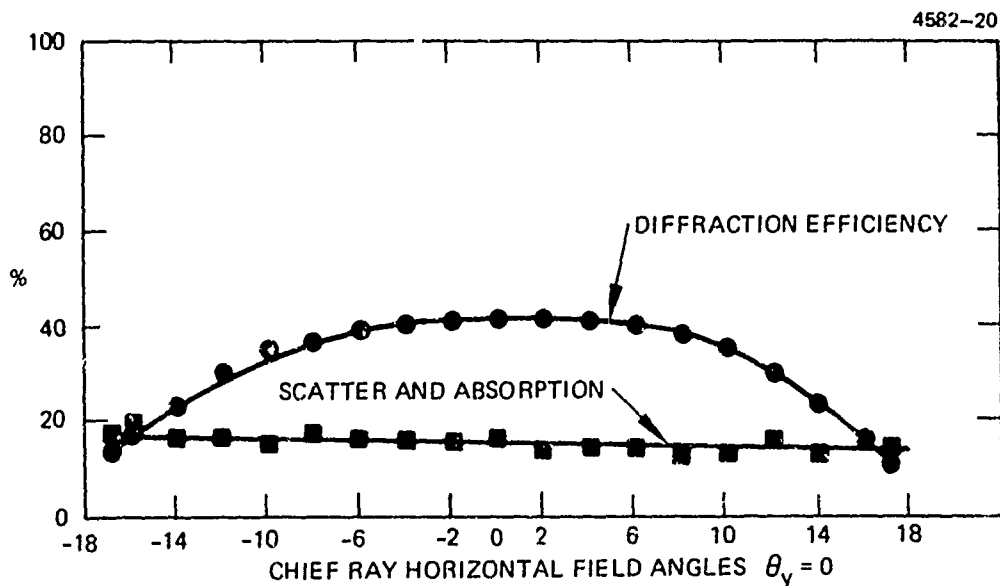


Fig. 17. Vertical and horizontal chief ray efficiency and scatter.

VI. Reflection Hologram Collimator/Combiner Design Study

A. Introduction

1. BACKGROUND, OBJECTIVE AND APPROACH

The major objective of the NADC-HHUD Optical Design Study is to establish the limits on the use of flat reflection hologram lenses in head-up display.

The principal elements in the Holographic Heads-Up Display (HHUD) are schematically illustrated in Figure 18. An intermediate image of the object surface is formed by a relay lens. This intermediate image is located at the focal surface of a flat plate holographic optical element which is used as an eyepiece to present a collimated image of the object to the eyes located in the exit pupil. The relay lens is located close to the entrance pupil to the holographic lens in order to minimize its size.

The reflection efficiency of the holographic element is highly wavelength and angle dependent. The holographic element therefore performs the dual functions of (a) eyepiece for the display and (b) combiner glass so that the display is viewed against the outside world seen through the holographic element. The angular sensitivity of the holographic element's reflection efficiency requires that the holographic element be constructed with point sources located close to the desired entrance and exit pupils. This ensures that high reflection efficiency of the chief rays occurs and a wide field of view (FOV) optical system is obtained.

The major objective of the NADC-HHUD Optical Design Study has been to establish the limits on the use of a flat reflective holographic optical element in the head-up display (HUD) configuration described above. To this end, the study was divided into two phases: The first was a general parametric study of flat holograms operating in a reflective mode, see Section VI-B. The principal parameters of interest were 1) the off-axis angle, ϕ , and focal length, f , of the holographic element, 2) tilts and curvatures of the focal surfaces, and 3) the amount of coma present. From the information gained in this phase of the study, a holographic configuration of optimum parameters was chosen as the starting point for the second phase of the study - the design of a complete head-up display.

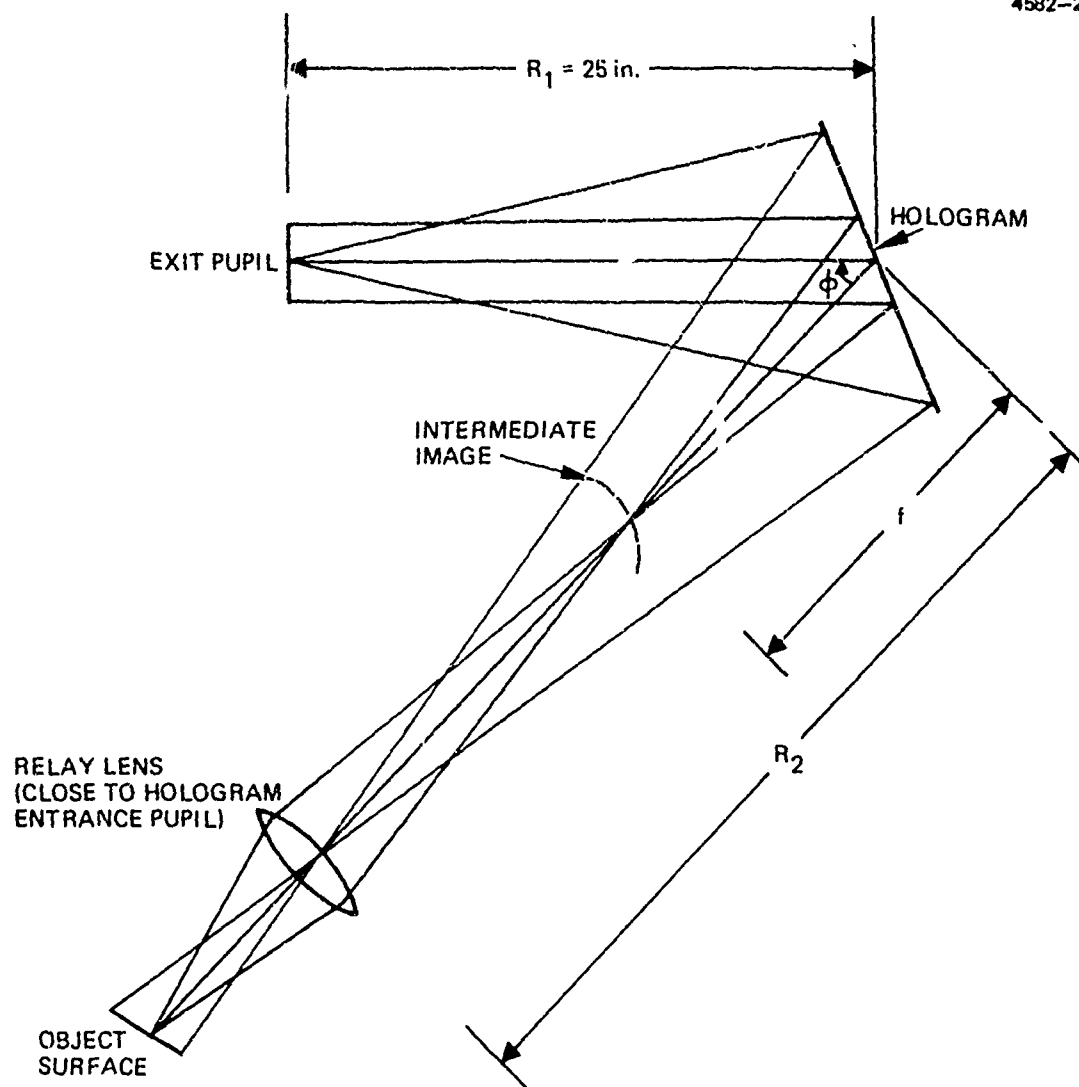


Fig. 18. HHUD optical concept and paraxial considerations in hologram parametric tradeoff.

VI. Reflection Hologram Collimator/Combiner Design Study

A. Introduction

2. DESIGN OBJECTIVES AND RESULTS

Pupil errors in the final configuration of the HHUD design were held to less than 5 mrad over the 25° FOV from a 3" high by 5" wide "racetrack" exit pupil at an eye relief of 25 inches.

Design objectives for the display are given in column I, Table 8. The field of view is large (± 12.5 deg.), as is the exit pupil (3 in. x 5 in.). Performance objectives were in the form of requirements for binocular disparity and collimation error (or accuracy). The results of the design effort are shown in column II, Table 8. The present design nearly meets the requirements over the entire field of view and over a "racetrack" shaped exit pupil of 5 in. major axis and 3 in. minor axis. Larger errors, exceeding 5 mrad, exist outside the "racetrack," i.e., in the extreme corners of the 3 in. x 5 in. rectangular pupil. This degradation at the outer corners is thought to be a limitation imposed by the present relay lens design rather than a property of the holographic element. The effective f-number of the relay lens is $f/0.95$ for the diagonal dimension of the pupil; this f-number is very low, and it stretches the limits of the triplet derivative used for the relay lens design.

The final configuration of the HHUD design has the following additional principal features: (1) a curved folding mirror to improve packaging and to reduce the relay lens size, and (2) cylindrical and tilted surfaces in the relay lens to compensate for aberrations in the holographic element. This design evolved with no guidelines for a cockpit envelope and should be treated as such. The geometry can be varied within limits and can be configured to fit in aircraft with large cockpits such as helicopters. Flat plate HHUD designs for fighter cockpits would probably require giving up some vertical FOV or exit pupil size.

Table 8. HHUD Optical Design Objectives and Results

Parameter	I. Objective		II. Value	
	Horizontal	Vertical	Horizontal	Vertical
Field of View, deg.	25	25	25	25
Exit Pupil, in.	5	3	5*	3*
Eye Relief, in.	25	25	25	25
System EFL, in.	9	9	9	9
System f-Number	1.8	3.0	1.8	3.0
Object Surface Diameter, in.	4	4	4	4
Object Surface Tilt, deg.	-	-	0	17.4
Hologram EFL, in.	-	-	14.9	14.9
Hologram Off-Axis Angle, deg.	-	-	0	43
Hologram Size, in.	-	-	~ 16	~ 15
Relay Lens Magnification	-	-	1.66	1.66
Relay Lens Size, in.	-	-	~ 5	~ 4
Resolution, mr.	1	1	< 1	< 1
Optical Efficiency	80%	80%	88% ⁺	88% ⁺
Binocular Disparity, mr.				
a) over central 15°	2.5	1.0	~ 2.0	~ 2.0
b) 15° to 25°	2.5	1.0	~ 2.5	~ 2.5
Collimation Error (accuracy), mr.				
a) over central 15°	1.0	1.0	~ 1.5	~ 1.5
b) 15° to 25°	1.0	1.0	~ 2.0	~ 1.5

*Nominal racetrack shape

+ Peak value; 60% average across pupil

VI. Reflection Hologram Collimator/Combiner Design Study

B. Parametric Study

1. SCOPE OF THE PARAMETRIC STUDY

The scope of the parametric study was defined by general paraxial considerations of the $f\#$ and size of the hologram and relay as related to the pupil locations and hologram focal length.

The scope of the parametric study was set by general paraxial considerations. These considerations, as illustrated in Figure 18 are a) the location of the pupils and the hologram focal length, b) the hologram and relay lens f -numbers, and c) the diameter of the relay optics.

To maintain maximum efficiency over the entire field of view, it is necessary to construct the hologram using point sources located near the entrance and exit pupils to be used in the display configuration. The distance from the exit pupil to the hologram, R_1 , is required to be 25 inches, see Table 8. The entrance-pupil-to-hologram length, R_2 , and the focal length, f , are then related by

$$\frac{1}{f} = \frac{1}{R_1} + \frac{1}{R_2}$$

and the f -number of the hologram, F_H , is

$$F_H = f/D$$

where D is the exit pupil dimension. Further, the nominal size of the relay lens, D_R , is determined by the size of the hologram exit pupil; the effective f -number of the relay lens, F_R , is determined by F_H and F_S where F_S is the overall optical system f -number:

$$D_R = \frac{R_2}{R_1} D$$

$$\frac{1}{F_R} = \frac{1}{F_S} + \frac{1}{F_H}$$

Figure 19a shows generally how the f -number of the hologram and the relay are related to R_2 and the hologram focal length, f . The relay can be seen to be very fast for small R_2 (small f).

Figure 19b shows how large the diameter of the relay optics can get for large R_2 (large f).

With these facts in mind, the scope of the parametric study was defined in terms of two properties: The hologram focal length and the off-axis angle, ϕ . Holograms with focal lengths of 10, 12, 14, and 16 inches and off-axis angles of 20, 40, 60 and 80 degrees were investigated. Counting all possible combinations, the study involved 16 different configurations.

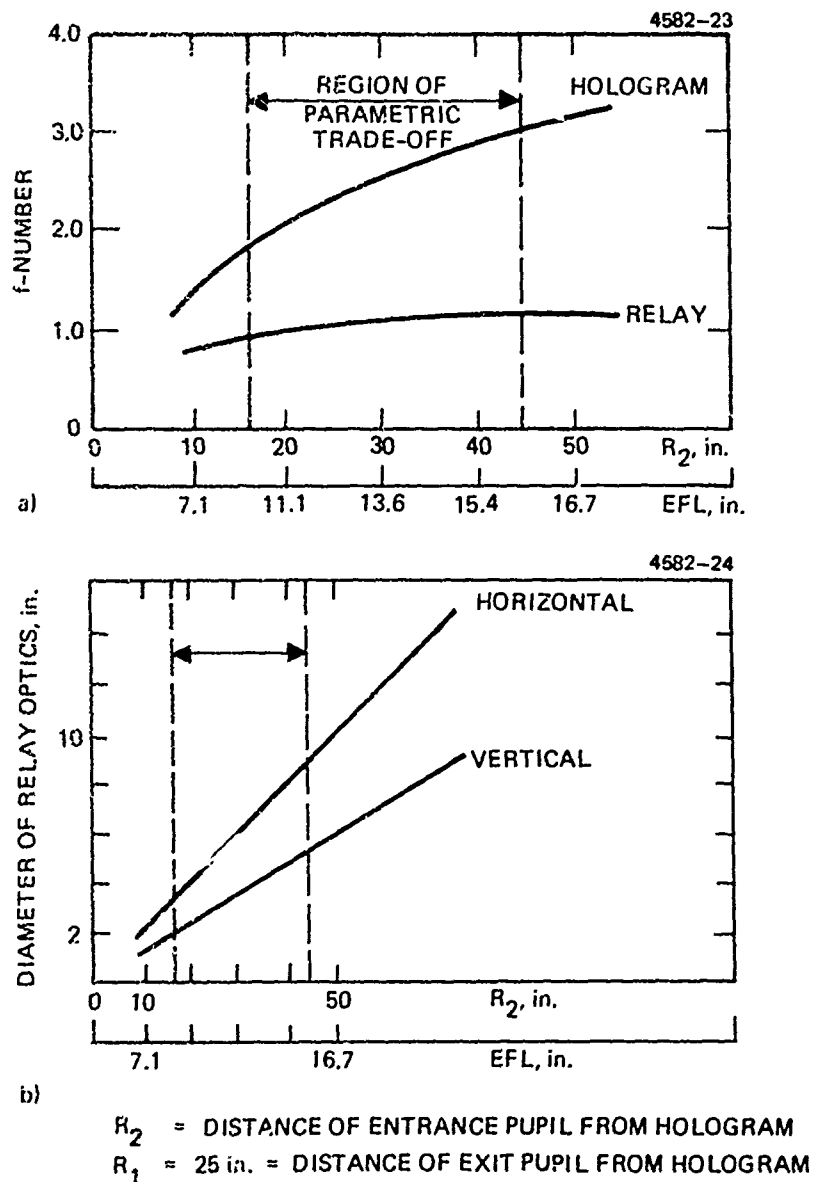


Fig. 19. Paraxial interrelationships between (a) hologram and relay lens f-numbers and (b) hologram focal length and relay lens size.

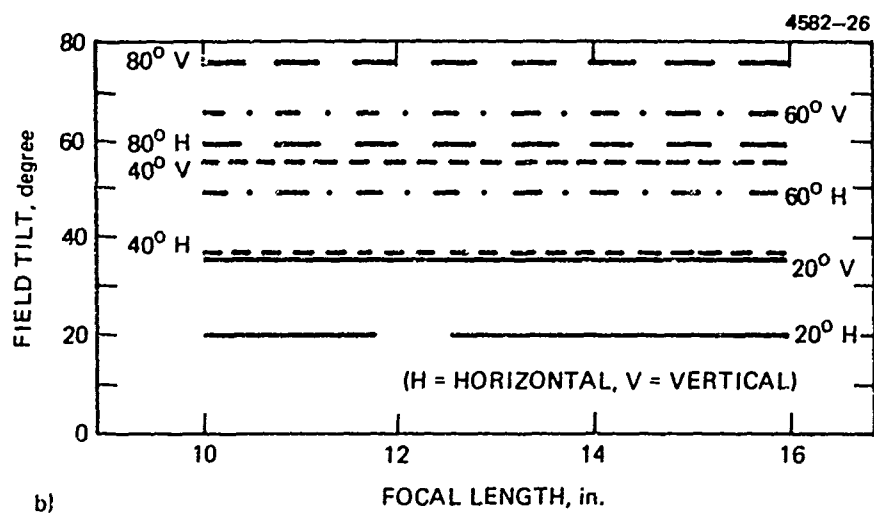
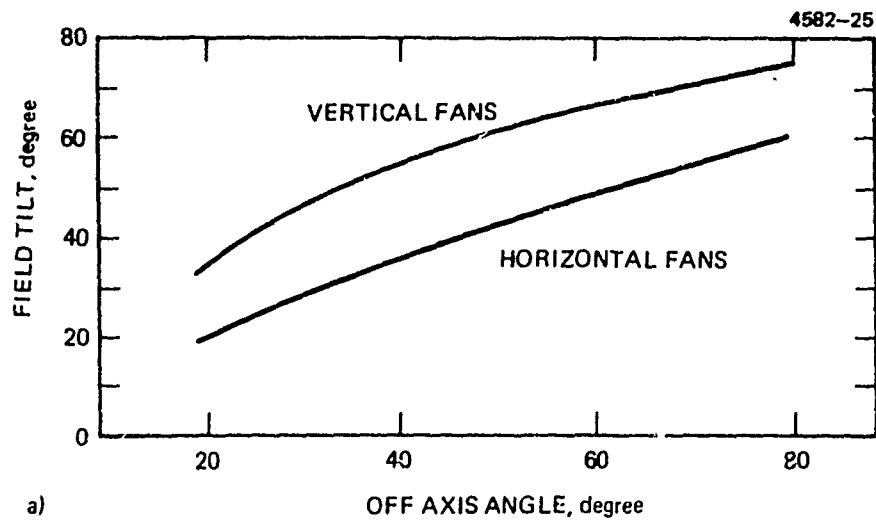
VI. Reflection Hologram Collimator/Combiner Design Study

B. Parametric Study

2. FOCAL SURFACE TILTS

The focal surface tilts of off-axis holograms increase with increasing off-axis angle and are nearly independent of focal length.

Focal surface tilts of off-axis holograms in general have two separate focal surfaces, one for fans of rays traced in the plane of symmetry (horizontal) and one for fans of rays traced in the plane of asymmetry (vertical). These two focal surfaces are tilted with respect to the optical axis. The direction of the tilts tends to bring the focal surfaces parallel to the hologram. More importantly, the focal surface defined by vertical fans is tilted at a greater angle than the surface defined by horizontal fans. This disparity in tilts is quite a problem because there can only be one tilt to the object surface; the problem is ultimately solved with cylindrical elements in the relay. Figure 20 shows that both focal surface tilts increase with increasing off-axis angle and are nearly independent of focal length.



NOTE: 40° H = 40° OFF AXIS, HORIZONTAL FANS

Fig. 20. Variation of field tilt. (a) off-axis angle. (b) Focal length.

VI. Reflection Hologram Collimator/Combiner Design Study

B. Parametric Study

3. FIELD CURVATURES

Reconciling field curvatures of the toroidal focal surfaces is a major factor in choosing the holographic lens configuration.

Field curvature — in addition to being tilted, the focal surfaces are generally toroidal, i.e., having different horizontal and vertical curvatures. Reconciling these four curvatures was a major factor in choosing a baseline holographic configuration.

Figures 21 and 22 point out the wide variation in field curvatures. However, it should be noted that the differences between the four curvatures is minimized when the focal length is in the region of 14 to 16 inches and the off-axis angle is about 40 to 60 degrees. In particular, the curves shown in Figures 21 and 22 intersect at certain points at which two of the four field curvatures are equal. It is important to obtain nearby equal field curvatures because large inequalities are very difficult to correct in the relay lens.

Figure 23 is an alternate way of graphing the information about field curvatures and makes use of the intersections of curves on Figures 21 and 22. Reference to the legend on Figure 23 shows that lines A, B, C and D represent conditions (values of focal length and ϕ) where certain field curvatures are equal. Of interest is the near-intersection of lines A, C and D. In this region, three of the four field curvatures are equal. This situation where three field curvatures are equal is also obtained at the intersection of lines B and C. From an optical design standpoint, this equality of field curvatures is very desirable.

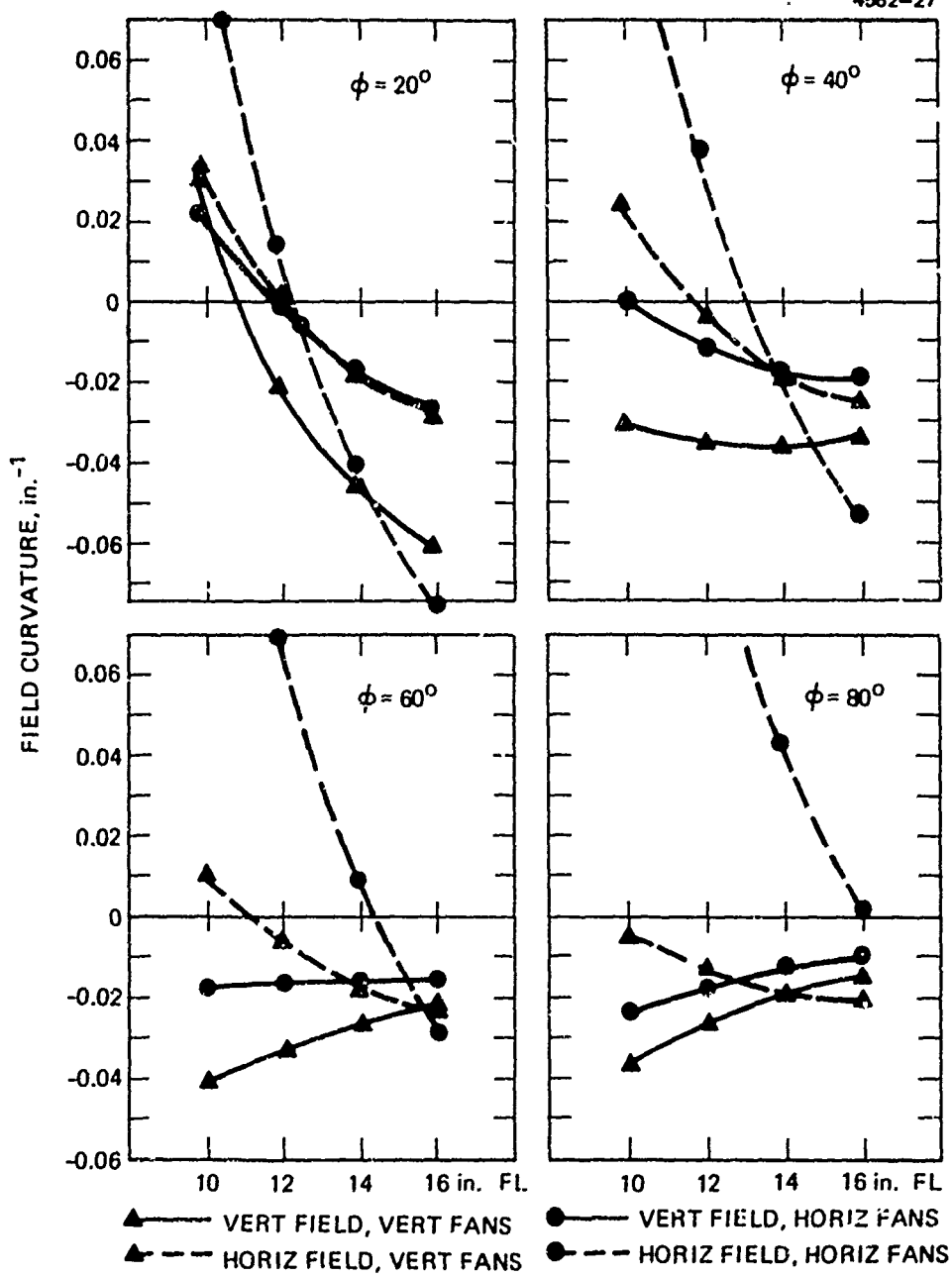


Fig. 21. Variation of field curvatures with focal length for different off-axis angles, ϕ .

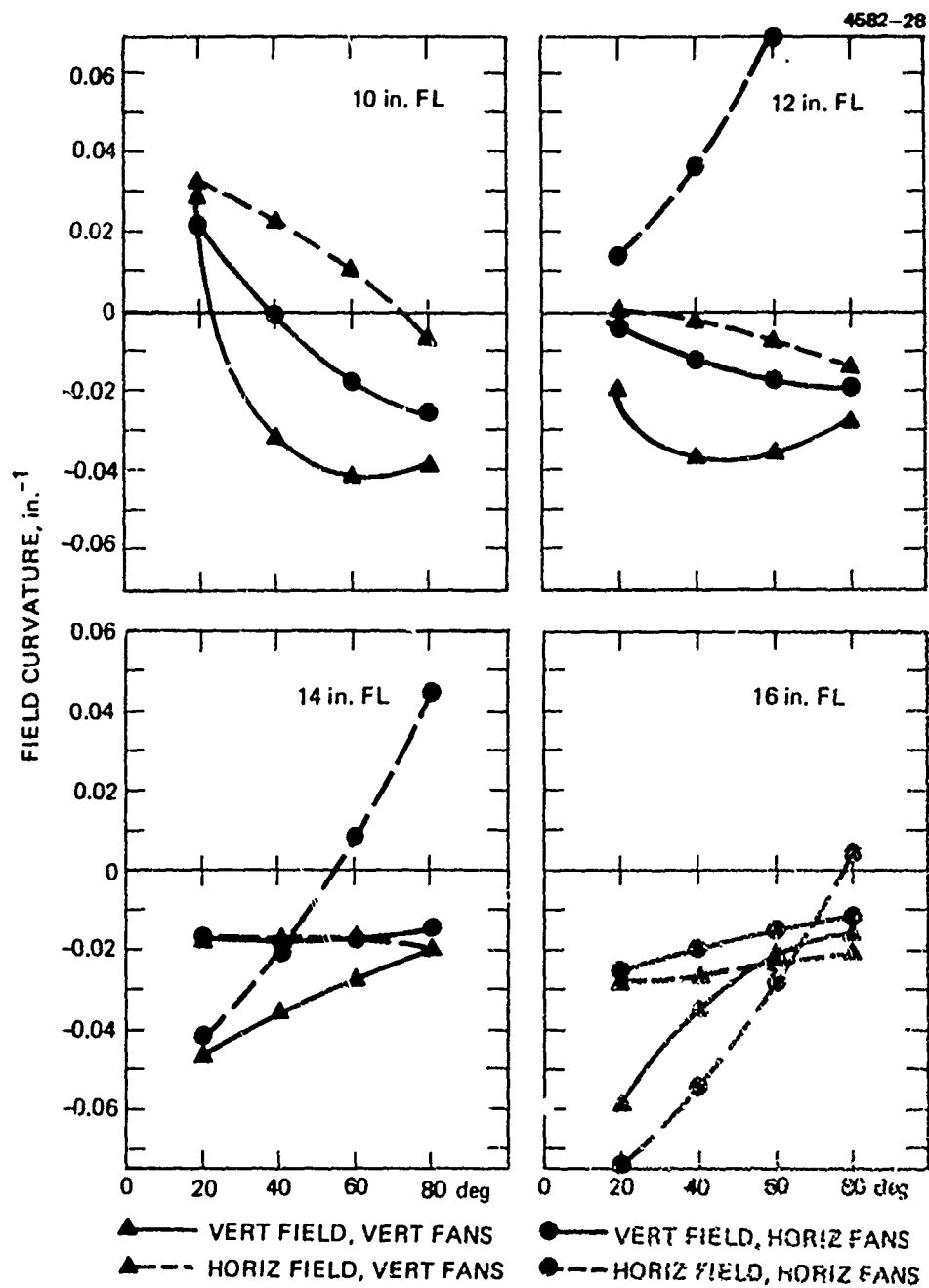
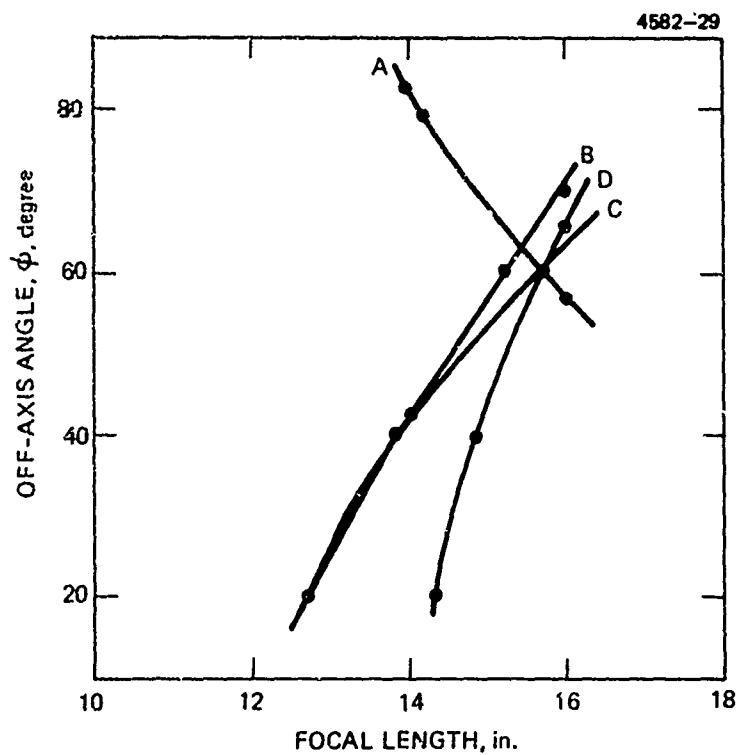


Fig. 22. Variation of field curvatures with off-axis angle for different focal lengths.



- A - HORIZONTAL AND VERTICAL CURVATURES DEFINED BY VERTICAL FANS ARE EQUAL
- B - HORIZONTAL AND VERTICAL CURVATURES DEFINED BY HORIZONTAL FANS ARE EQUAL
- C - HORIZONTAL CURVATURE DEFINED BY VERTICAL FANS = HORIZONTAL CURVATURE DEFINED BY HORIZONTAL FANS
- D - VERTICAL CURVATURE DEFINED BY VERTICAL FANS = HORIZONTAL CURVATURE DEFINED BY HORIZONTAL FANS

Fig. 23. Selection of near equal field curvatures.

VI. Reflection Hologram Collimator/Combiner Design Study

B. Parametric Study

4. ABERRATIONS

Coma, the dominant aberration in symmetric reflection holograms, is minimized for small off-axis angles and large focal lengths.

Aberrations — Coma is the dominant aberration, but some spherical aberration is also present. The holograms considered in the trade-off were constrained to operate in a symmetric fashion, where the normal of the hologram bisects the off-axis angle. This arrangement eliminates axial astigmatism and minimizes dispersion. Small off-axis angles and large focal lengths are indicated by Figures 24 for the minimization of coma. Further, at large focal lengths the coma is nearly constant across the field of view.

In addition to the above, there exists an aberration made apparent by fans traced from horizontal object points. There is a total lack of symmetry across the pupil of these fans, which causes horizontal image errors for fans of rays traced in the vertical section, and vertical image errors for fans of rays traced in the horizontal section. These image errors are usually small in concentric optical systems, but have to be considered during the optimization of a highly off-axis optical system. They were not considered as part of the holographic element trade-off, but were compensated for during the HHUD optical system design.

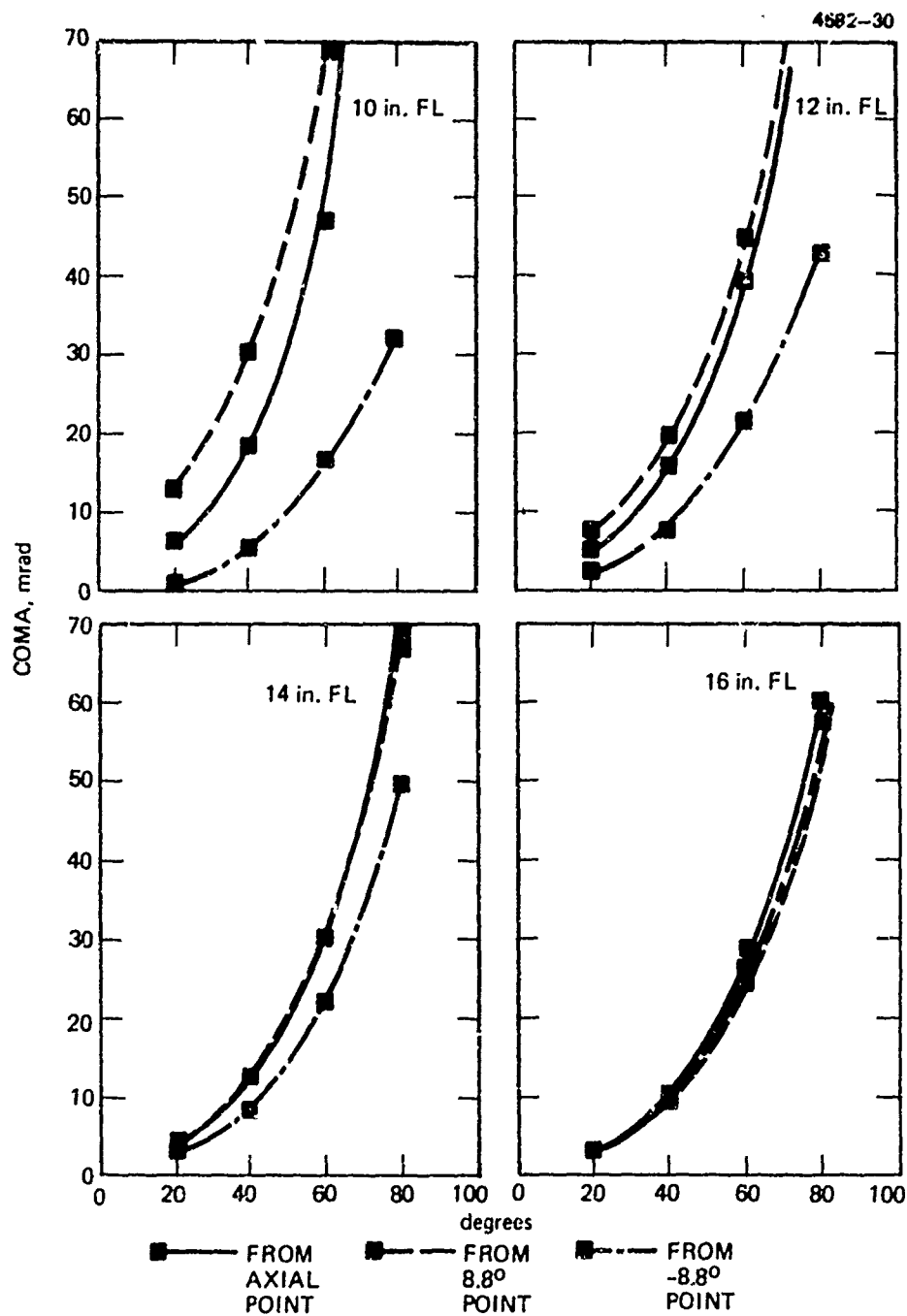


Fig. 24. Variation of coma with off-axis angle for different focal lengths.

VI. Reflection Hologram Collimator/Combiner Design Study

C. Baseline Hologram

1. PARAMETERS

The baseline hologram is a 43° off-axis symmetric reflection hologram lens with a focal length of 14.9 inches.

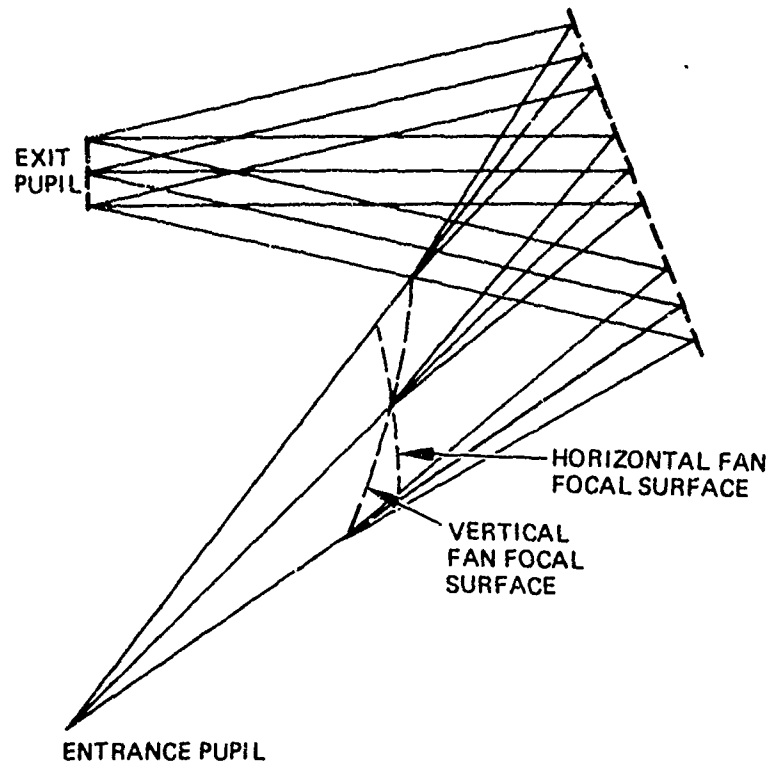
The parameters chosen for the baseline hologram are a focal length of 14.9 in. and an off-axis angle of 43° . Two of the four field curvatures are equal. Column I of Table 9 summarizes the properties of this baseline hologram. Figure 25a shows the pupils of the hologram along with intermediate focal surfaces formed by vertical fans.

While we were not constrained to any particular cockpit geometry in this design, it was reasonable to assume that (a) a fold would be needed in the optical path between the entrance pupil and the hologram, and (b) the large focal length implied an overly large relay lens. Using a mirror with some optical power to make this fold, we were able to reduce the pupil-to-hologram distance from 36.9 inches to 29.9 inches. Another result of the addition of the folding mirror, and one having an even greater impact on the design, was the reduction in the size of the relay elements from approximately 7.5 inches to about 5 inches. Reference to column II of Table 9 shows that the curved folding mirror produced other small changes and indeed helped the balancing of field curvatures. The hologram and folding mirror produced other small changes and indeed helped the balancing of field curvatures. The hologram and folding mirror are pictured in Figure 25b.

TABLE 9. Properties of Baseline Hologram

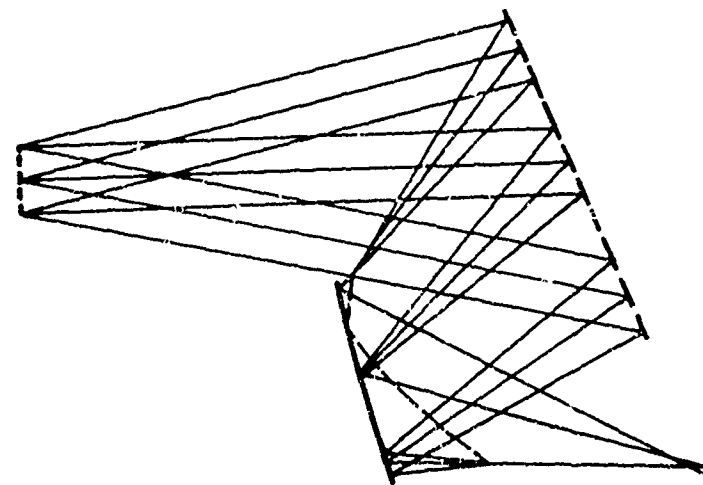
Property	I Before Folding Mirror	II After Folding Mirror
Off-Axis Angle, deg.	43	43
Focal Length, in.	14.90	14.86
R_2 , Entrance Pupil to Hologram, in.	36.9	29.9
Implied Relay Size, in.	~ 7.5	~ 5.0
For Vertical Fans		
Field Tilt, deg.	56.7	56.6
Vertical Radius, in.	29.6	20.6
Horizontal Radius, in.	46.2	23.7
For Horizontal Fans		
Field Tilt, deg.	37.5	38.2
Vertical Radius, in.	53.6	25.7
Horizontal Radius, in.	29.8	19.7

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A) WITHOUT FOLDING MIRROR

4682-32



B) WITH FOLDING MIRROR

Fig. 25. Vertical section of hologram.

VI. Reflection Hologram Collimator/Combiner Design Study

C. Baseline Hologram

2. GEOMETRICAL ABERRATIONS

The geometrical aberrations, primarily coma, of the baseline hologram is approximately 13 mrad on axis.

The geometrical aberrations of the baseline holographic configuration are given in Figures 26a and 26b. As previously mentioned, coma dominates, amounting to about 13 mrad on axis. The aforementioned lack of symmetry for horizontal field points is clearly shown in Figure 26.

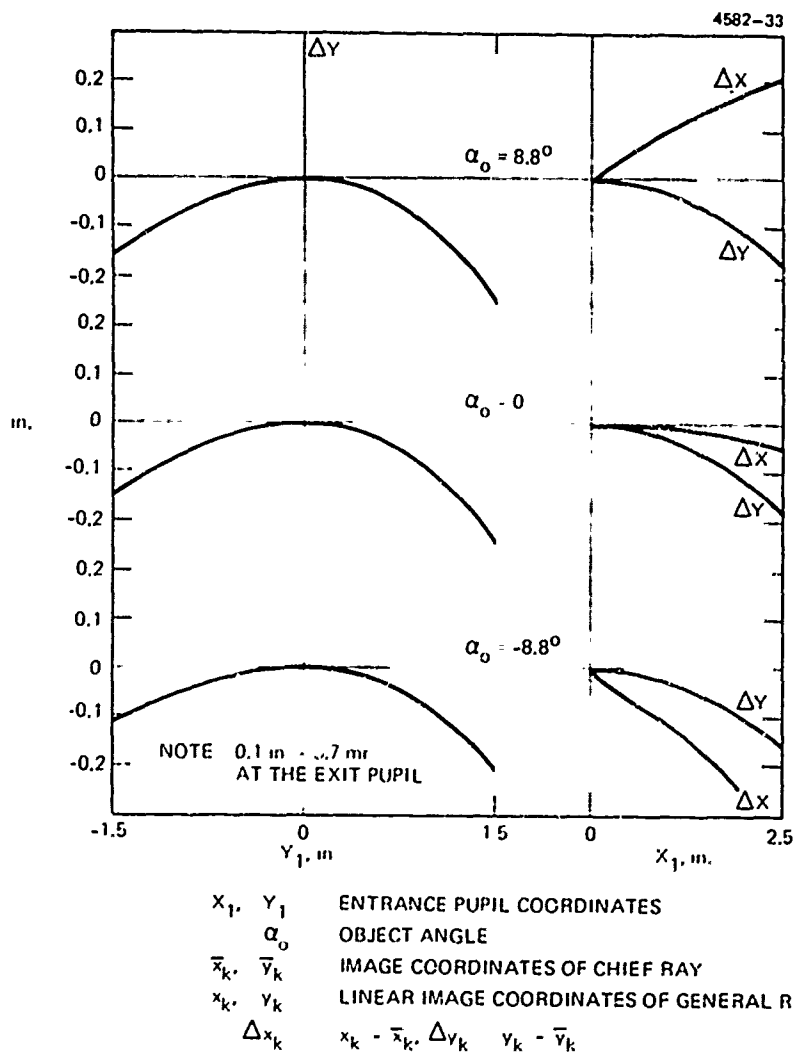


Fig. 26(a). Geometrical aberrations of baseline hologram for vertical field angles, α_0 .

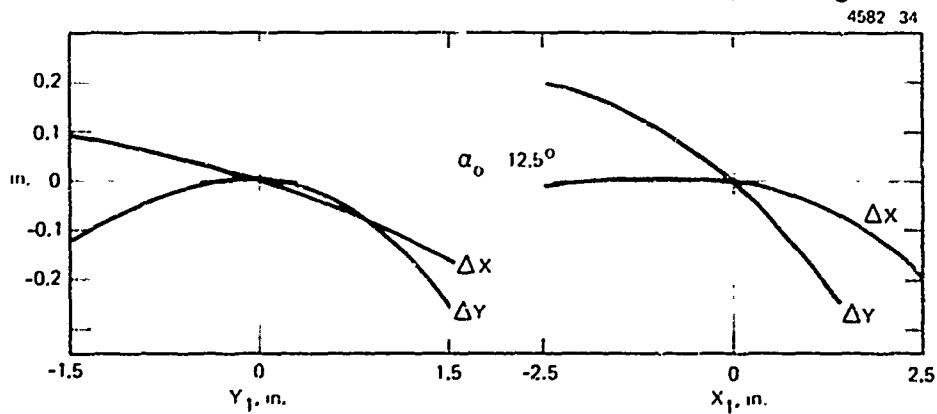


Fig. 26(b). Geometrical aberrations of baseline hologram for horizontal field angle of 12.5 degrees.

VI. Reflection Hologram Collimator/Combiner Design Study

C. Baseline Hologram

3. CONSTRUCTION BEAMS

The baseline hologram is constructed with point sources centered at the entrance and exit pupil of the HUD system.

The hologram is constructed using two point sources centered at the desired pupil locations. The beams associated with these points can be termed the reference beam and the object beam. The holographic element construction optics are shown in Figure 27. The reference beam simply diverges from point R located at the exit pupil. The object beam converges to point O at the entrance pupil. The $f/1$, 36 inch EFL spherical mirror in the object beam and the cylindrical elements in the object beam were designed, specified, and procured as part of Phase 2 of the Flyable Hologram Lens Development Program.³ These cylindrical elements are used to correct aberrations inherent in the off-axis use of the spherical mirror so that the aberrations in the object beam are insignificant.

4582-35

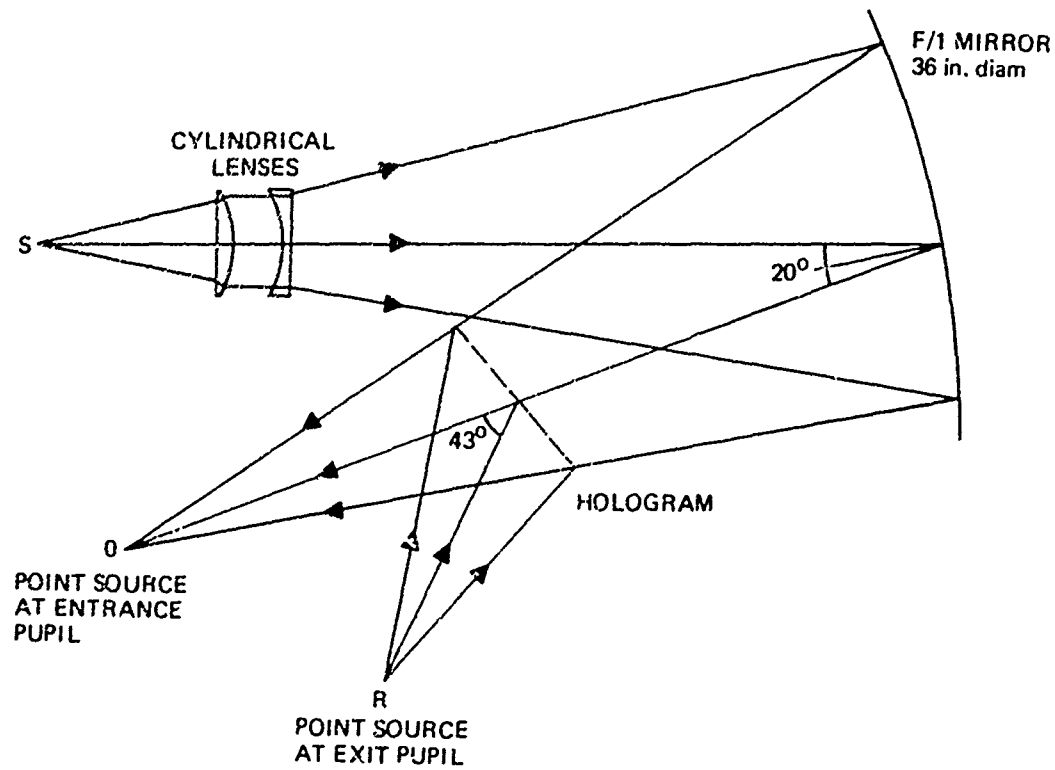


Fig. 27. Holographic element construction optics.

VI. Reflection Hologram Collimator/Combiner Design Study

D. HHUD Relay Lens Design

1. PRELIMINARY DESIGN

A Cooke triplet was chosen as a starting relay lens form used to image the object plane onto the focal surface of the hologram.

A relay lens is necessary to image the object plane onto the focal surface of the hologram. While the object plane may be either the diffusing screen of a laser spot scanner or the CRT display, exact method of display has little bearing on the design beyond the assumption of monochromaticity. Paraxial calculations showed that the relay lens must have those properties listed in Table 10. The relay lens is somewhat fast as was foreseen. A derivative of a Cooke triplet was chosen as a starting point (Figure 28), and the relay lens was optimized to roughly a 3 mrad system using a combination of 3rd order, 5th order, and real-ray aberrations. Figure 29 shows the geometrical aberrations of this interim relay.

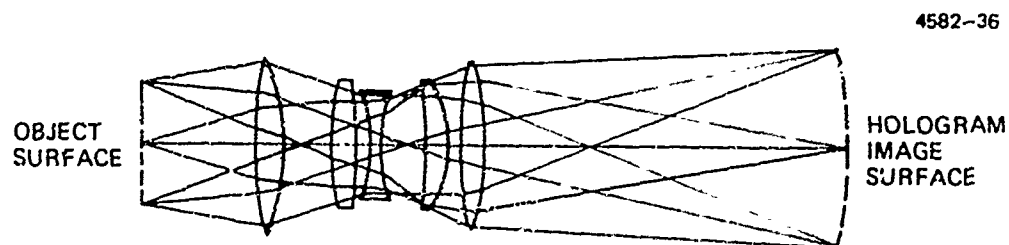


Fig. 28. Preliminary design of the relay lens.

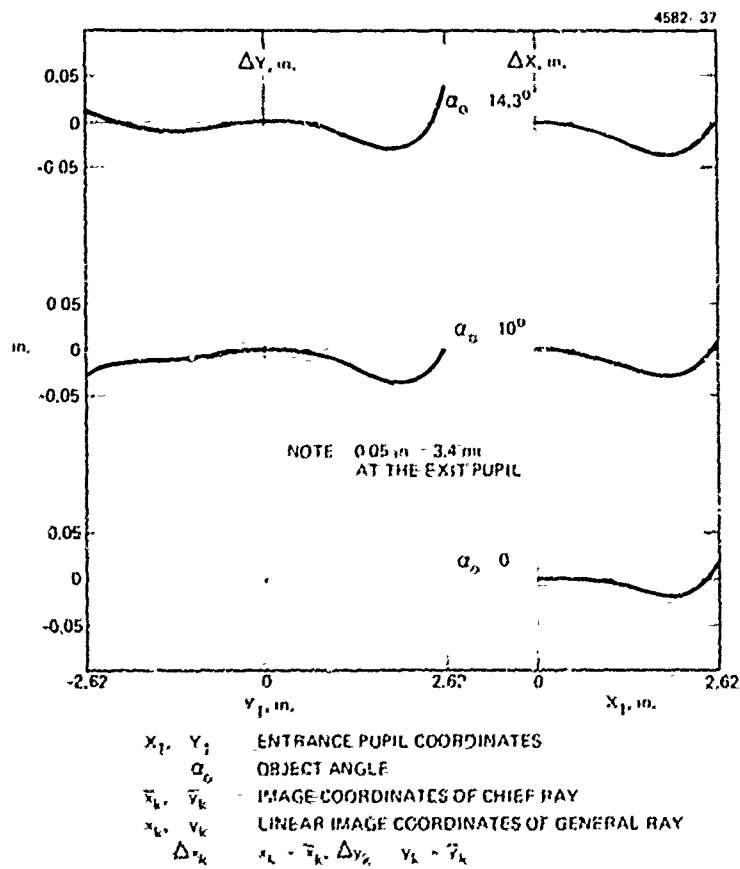


Fig. 29. Geometrical aberration at the intermediate image of the relay lens.

Table 10

Paraxial Properties of the Relay Lens

Characteristic	Value
Distance from Hologram,	29.9
Magnification	1.66X
Focal Length, in.	5.64
f-Number	
Horizontal	1.13
Vertical	1.88
Diameter of Optics, in.	5
Object Surface Size, in.	~ 4

VI. Reflection Hologram Collimator/Combiner Design Study

D. HHUD Relay Lens Design

2. OPTICAL SYSTEM DESIGN OPTIMIZATION

Optical system design optimization is performed on head-up display configuration, the combination of the baseline hologram geometry with a preliminary relay lens design.

At this point, with the hologram and relay lens designs established separately, what remained was to combine them in the head-up display configuration and perform the detailed optical system design optimization. Merely placing the relay lens at the entrance pupil of the hologram neglects the fact that the hologram has two separate image surfaces tilted at different angles. A method is needed by which the two could be made to coincide. It is preferable to find a means of controlling the focal surface defined by vertical fans, since it is tilted at a greater angle.

The solution to this problem involves the use of cylindrical lenses. A negative cylindrical lens was placed between the folding mirror and the relay, just after the hologram image surface, see Figure 30. It is tilted 22 degrees in the direction opposite to the tilt of the hologram image surface. Its orientation is such that the cylindrical axis is horizontal and the element is much closer to the hologram image surface at the bottom than at the top. The net effect is that the lens exhibits power for vertical fans and acts to set the focal surface (for vertical fans) in a more upright position. The focal surface for horizontal fans is also affected somewhat, so that the superposition of the two surfaces results in one which is tilted at approximately 45 degrees.

A second cylindrical lens, used to correct the astigmatism introduced by the first, is placed between the fourth and fifth elements of the relay lens; its cylindrical axis is also horizontal. The resulting HHUD could be deemed a 12 mrad system with coma as the dominant aberration.

The elimination of the large coma contribution and the final optimization of the system are the next concerns. Again, experience led us to believe that either decentering or tilting relay elements and surfaces would help to bring down the amount of coma. We determined that tilting surfaces offered a more efficient means of correction than decentering them. We were also able to "manually" approximate a solution well enough so that the automatic optimization procedure of the computer program had no trouble converging.

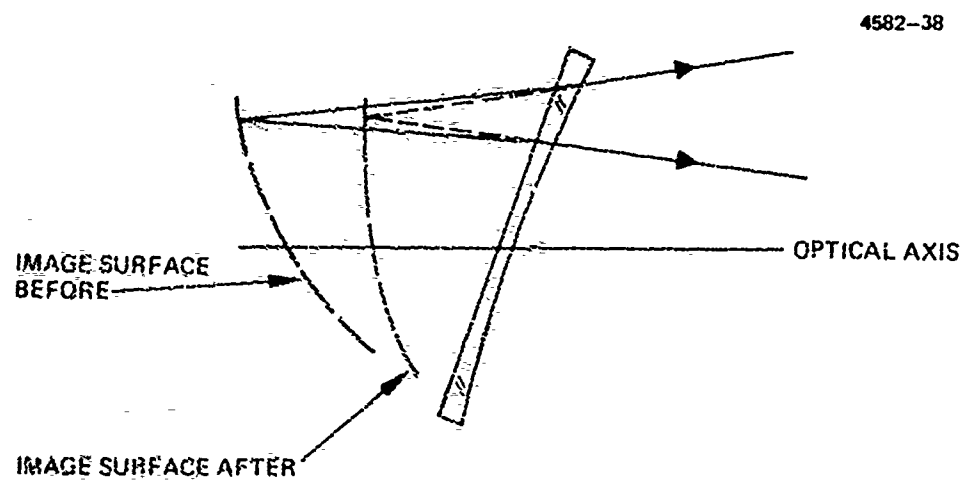


Fig. 30. Matching field tilts using a tilted cylindrical field lens.

VI. Reflection Hologram Collimator/Combiner Design Study

D. HHUD Relay Lens Design

3. HHUD OPTICAL SYSTEM

Geometrical aberrations of the final HHUD optical system are within 5 mrad along the 3 inches vertical and 5 inches horizontal axis of the pupil.

The resulting HHUD optical design is depicted in Figures 31 and 32. The object surface tilt has decreased from 32.4 to 17.4 degrees. The geometrical aberrations are shown in Figures 33a and 33b. With the possible exception of the -12.5 degree vertical field point, it would appear that we have a 1.5 to 2.0 mrad system. This conclusion is partially misleading, in that Figures 33a and 33b represent only those fans traced along the x and y axes of the pupil; no information is given about the rest of the 3 inch by 5 inch rectangle. A more detailed analysis covering the whole pupil and using the specified errors of binocular disparity and collimation error was therefore performed.

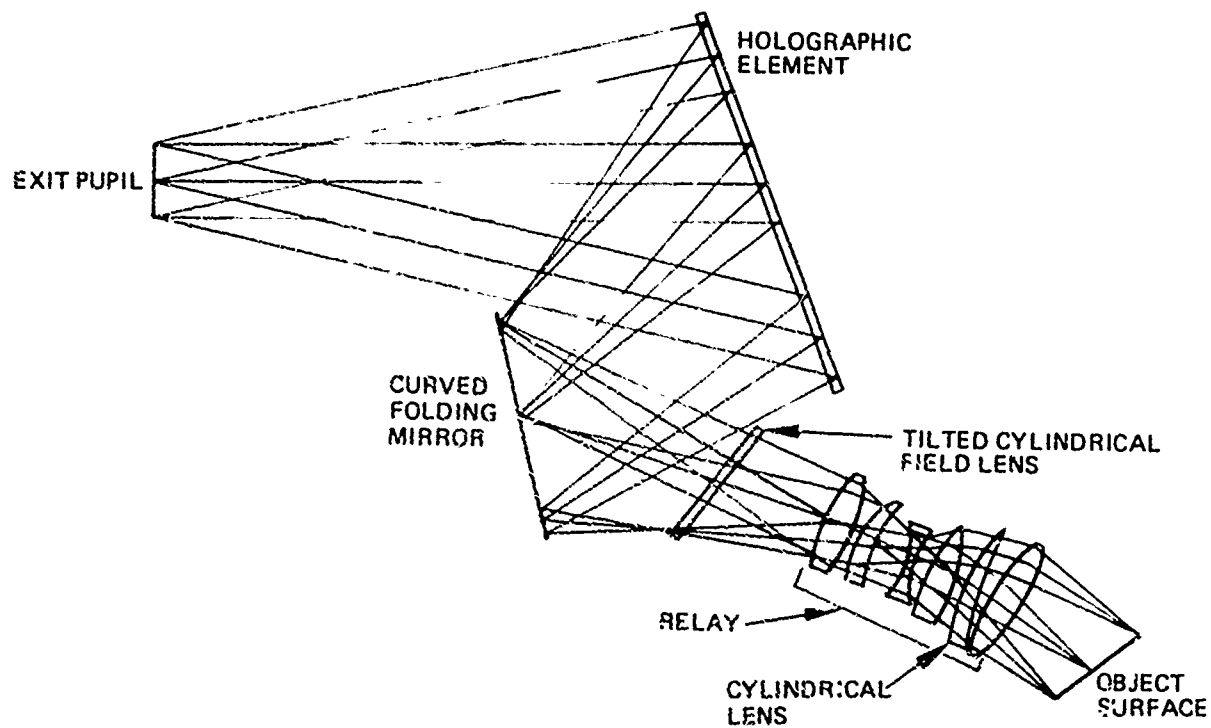


Fig. 31. Vertical section of HHUD.

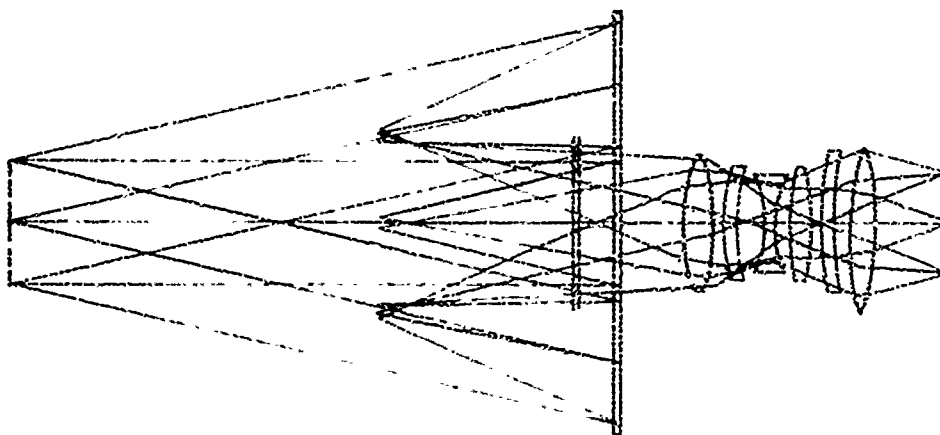


Fig. 32. Horizontal section of HHUD.

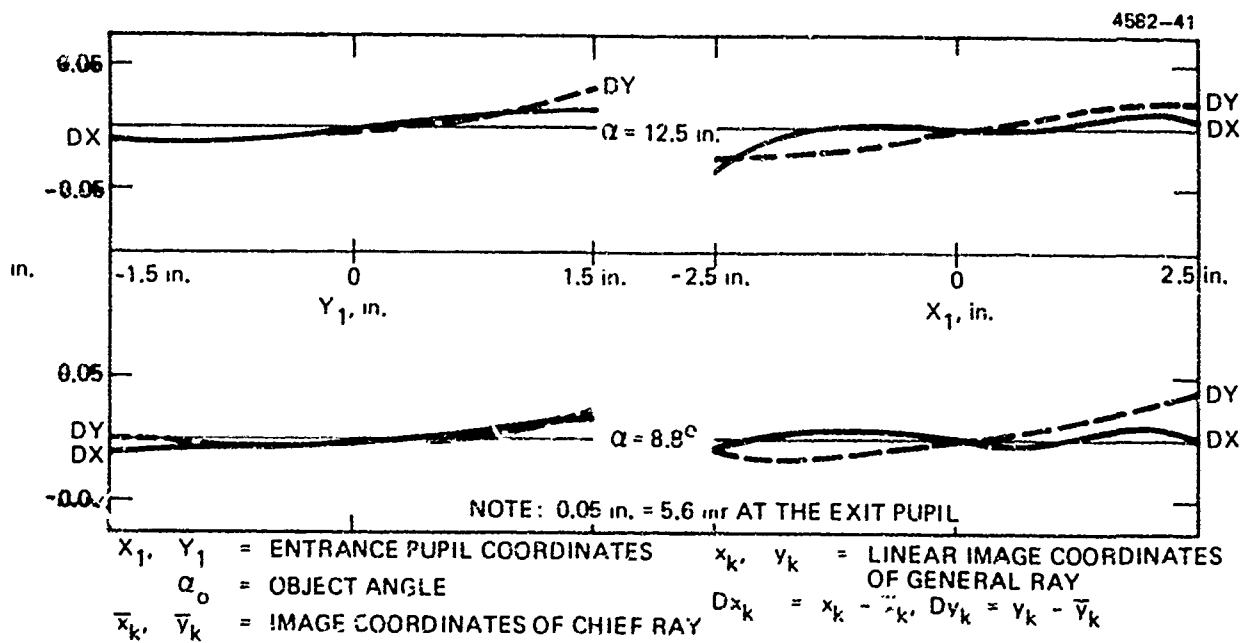


Fig. 33(a). Geometrical aberrations of HHUD (horizontal field angles).

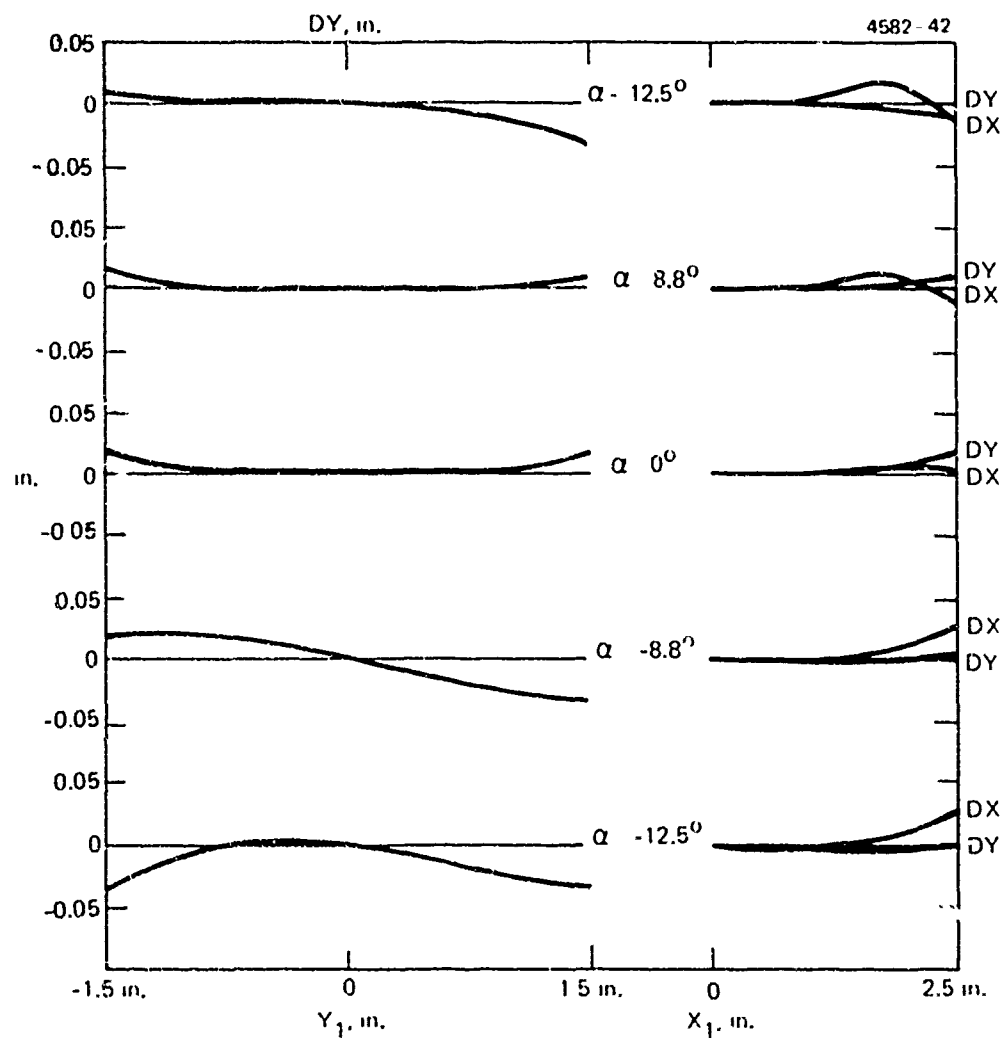


Fig. 33(b). Geometrical aberrations of HRPD (vertical field angles).

VI. Reflection Hologram Collimator/Combiner Design Study

E. HHUD Performance Evaluation

1. DEFINITION — BINOCULAR DISPARITY AND COLLIMATION ERRORS

Binocular disparity is a comparison of the image seen by the left eye to that seen by the right eye. Collimation error is a measure of the variation of image location.

Binocular disparity (BD) is a comparison of the image seen by the left eye to that seen by the right eye. If $D\alpha$ and $D\beta$ denote the horizontal and vertical angular deviations of a ray from the reference ray, and if "left" and "right" refer to the eyes, then horizontal and vertical binocular disparity are defined by (see Figure 34a):

$$BDX = D\alpha_{\text{left}} - D\alpha_{\text{right}}$$

$$BDY = D\beta_{\text{left}} - D\beta_{\text{right}}$$

Collimation error (CE), also called accuracy, measures the variation of image location, for a given point in the image, as the viewer's eye moves within the exit pupil. It is the variation in the average position of the point which is seen by both eyes and is defined by

$$CEX = (D\alpha_{\text{left}} + D\alpha_{\text{right}})/2$$

$$CEY = (D\beta_{\text{left}} + D\beta_{\text{right}})/2$$

The scheme used to evaluate these quantities over the whole pupil and for the entire field of view is described below, and is illustrated in Figure 34b. The first step is to choose a field angle. The degree of symmetry depends on whether the field angle is vertical or horizontal. For vertical field angles the system exhibits bilateral symmetry: only half of the pupil need be considered because the other half is identical. For horizontal field angles there is no symmetry and the performance across the whole pupil must be examined.

The second step is to trace rays across the pupil (or half

pupil) from the chosen field angle and evaluate the angular image errors, $D\alpha$ and $D\beta$. The rays are traced across the pupil in a raster fashion: left (L) to right (R), top to bottom along seven horizontal lines separated by 0.5 inch. Binocular disparity and collimation error are calculated from the above equations using two rays separated by an assumed interpupillary distance of 2.5 inches.

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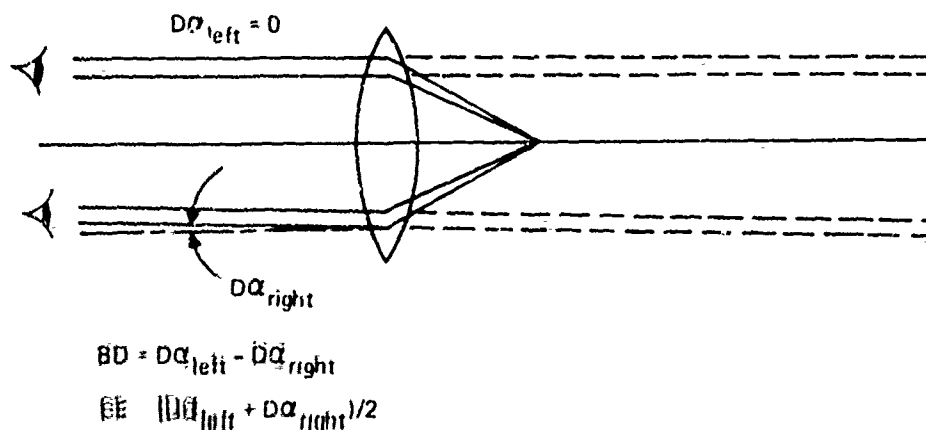


Fig. 34a. Definition of binocular disparity and collimation error.

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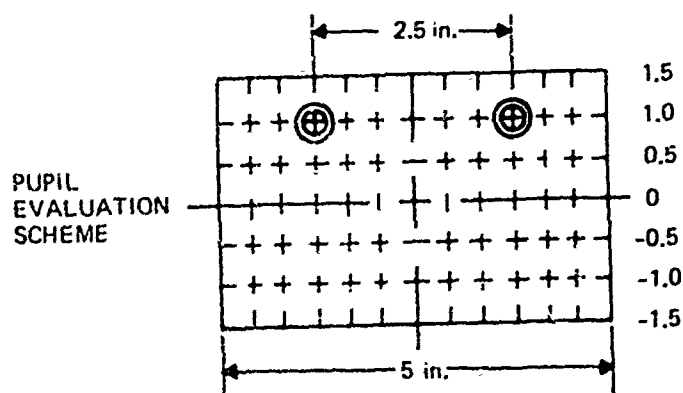


Fig. 34b. Rays traced through the exit pupil for the evaluation of BD and CE.

VI. Reflection Hologram Collimator/Combiner Design Study

E. HHUD Performance Evaluation

2. DATA - BINOCULAR DISPARITY AND COLLIMATION ERRORS

Over most of the 25° circular field and much of the 3" x 5" exit pupil of the designed HHUD system, pupil errors are within 1 or 2 mrad.

One can consult Figure 35 and find values for binocular disparity and collimation error, both horizontal and vertical. Each figure gives data for one field angle and sufficient eye positions to cover the whole pupil. Out of this large amount of information, some conclusions become clear:

- a. Over most of the field and much of the pupil, these curves agree with the geometrical aberrations shown in Figure 33a and b, i.e., that the system exhibits 1 to 2 mrad of error.
- b. Close inspection of Figure 35 shows that the significant departures from the 1 to 2 mrad level occur generally for the corners of the pupil. This is true for all field points.

To achieve the specified performance over the entire 3 x 5 inch rectangular pupil seems unlikely with the present design. It is therefore recommended that a racetrack shaped pupil be used; this pupil would have extreme dimensions of 3 inches vertical by 5 inches horizontal, but would not include the corners of the 3 x 5 inch rectangular pupil. As was mentioned previously, the drop in performance in the corners of the pupil is believed to be a limitation of the relay lens design form.

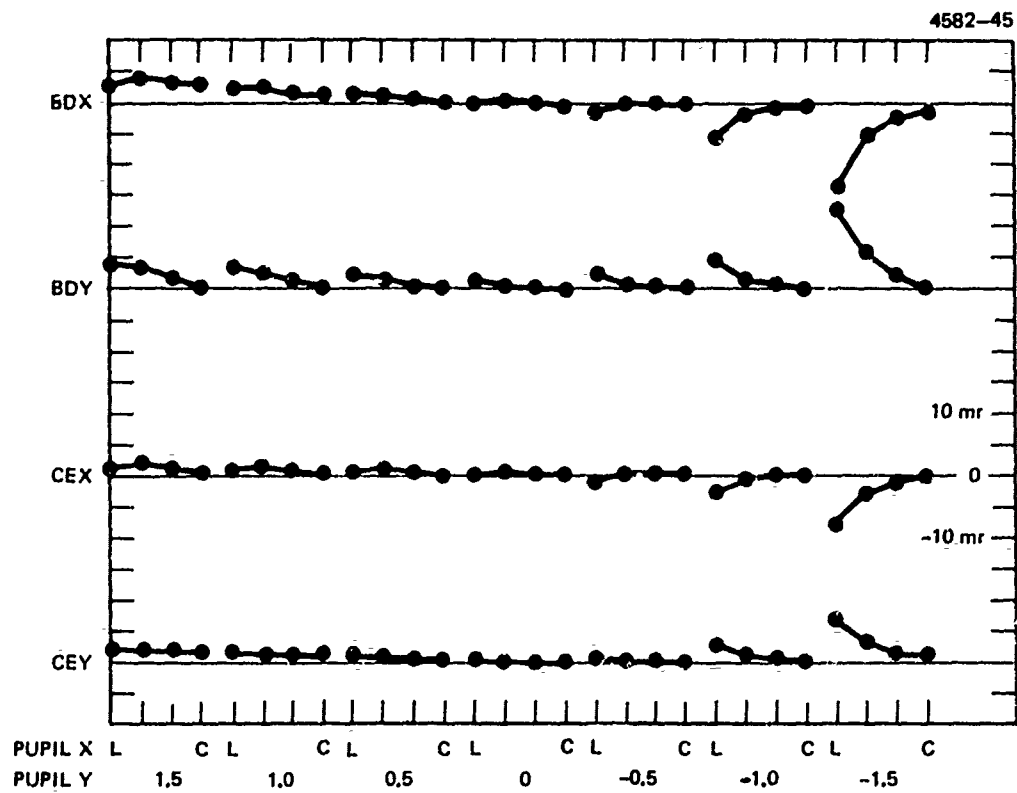


Fig. 35. Binocular disparity (BD) and collimation error (CE) on axis.

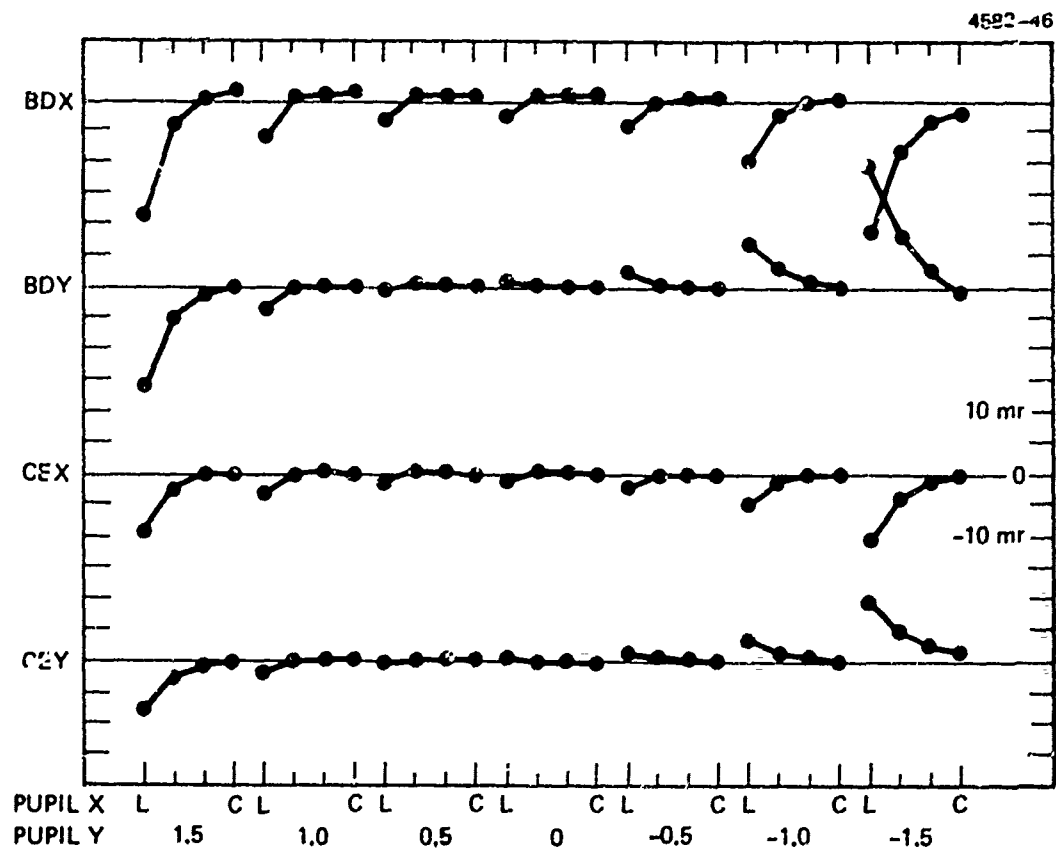


Fig. 35. Binocular disparity (BD) and collimation error (CE) at vertical field angle of 8.8 degrees.

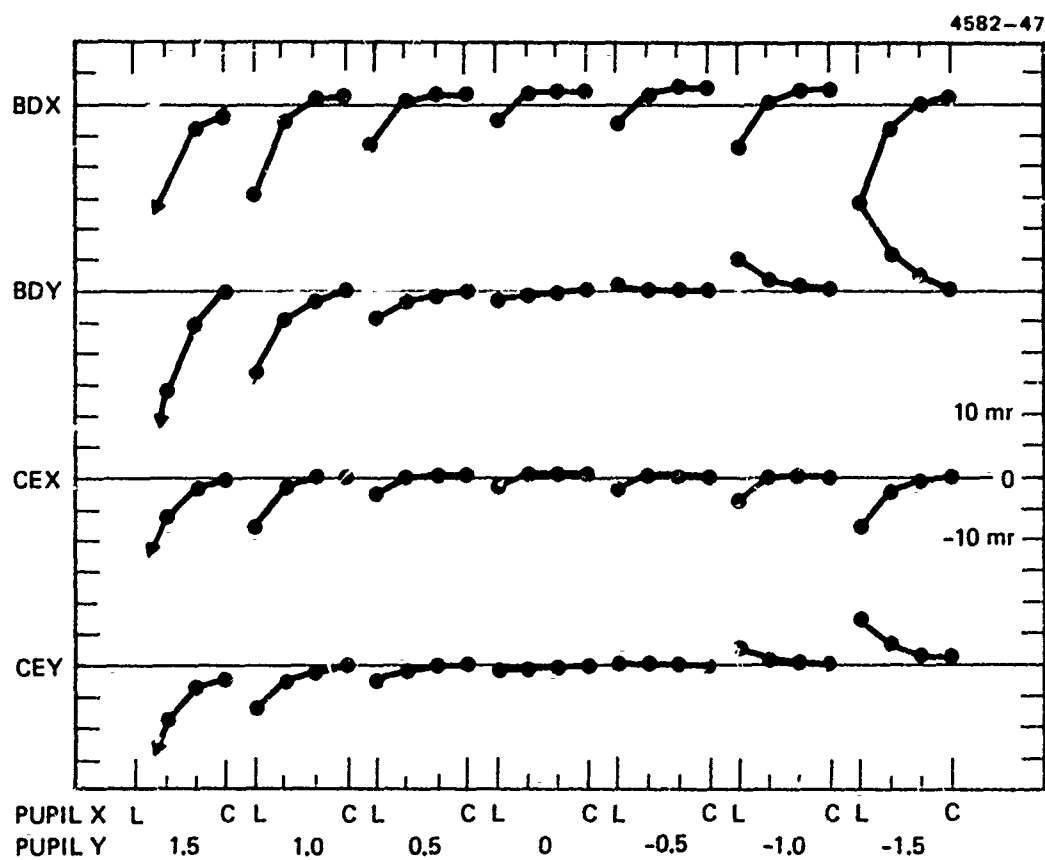


Fig. 35. Sinocular disparity (BD) and collimation error (CE) at vertical field angle of 12.5 degrees.

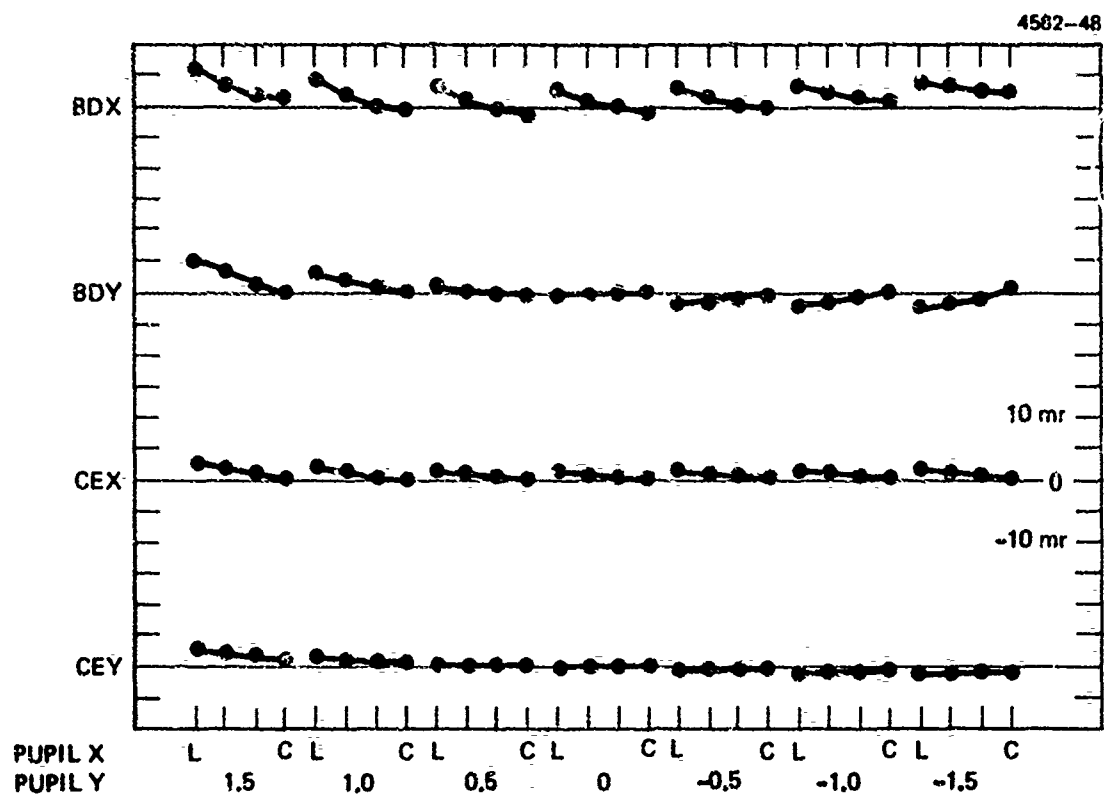


Fig. 35. Binocular disparity (BD) and collimation errors (CE) at vertical field angle of -12.5 degrees.

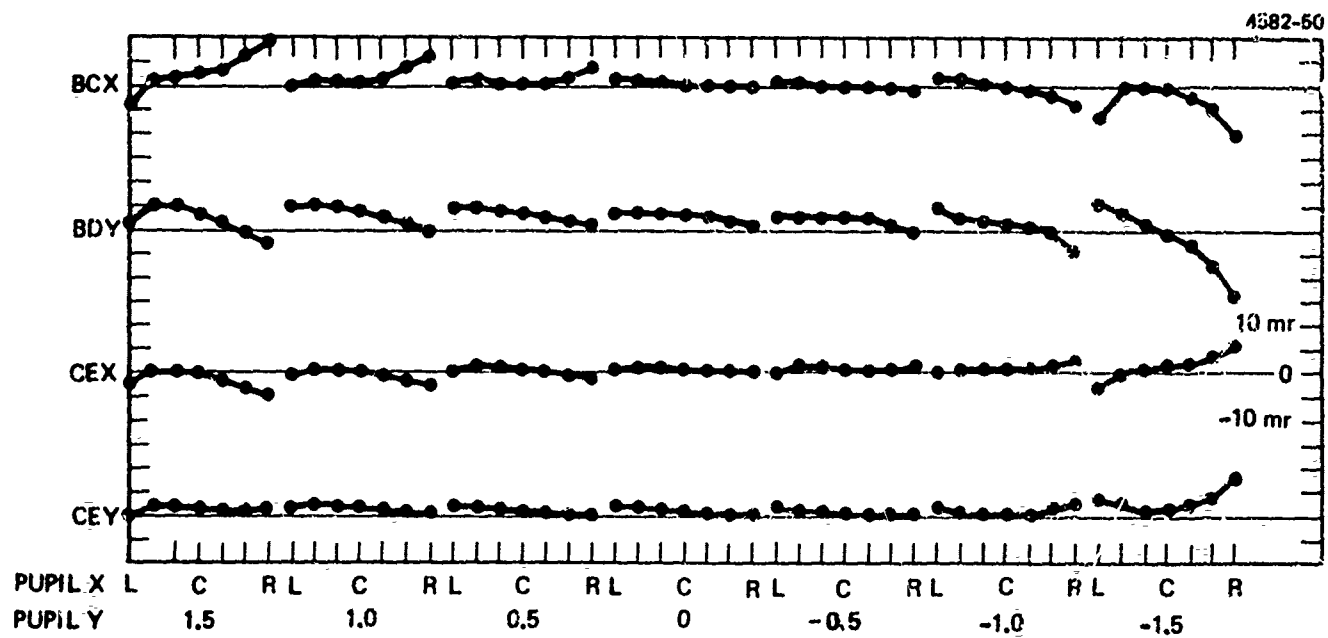


Fig. 35. Binocular disparity (BD) and collimation error (CE) at horizontal field angle of 8.8 degrees.

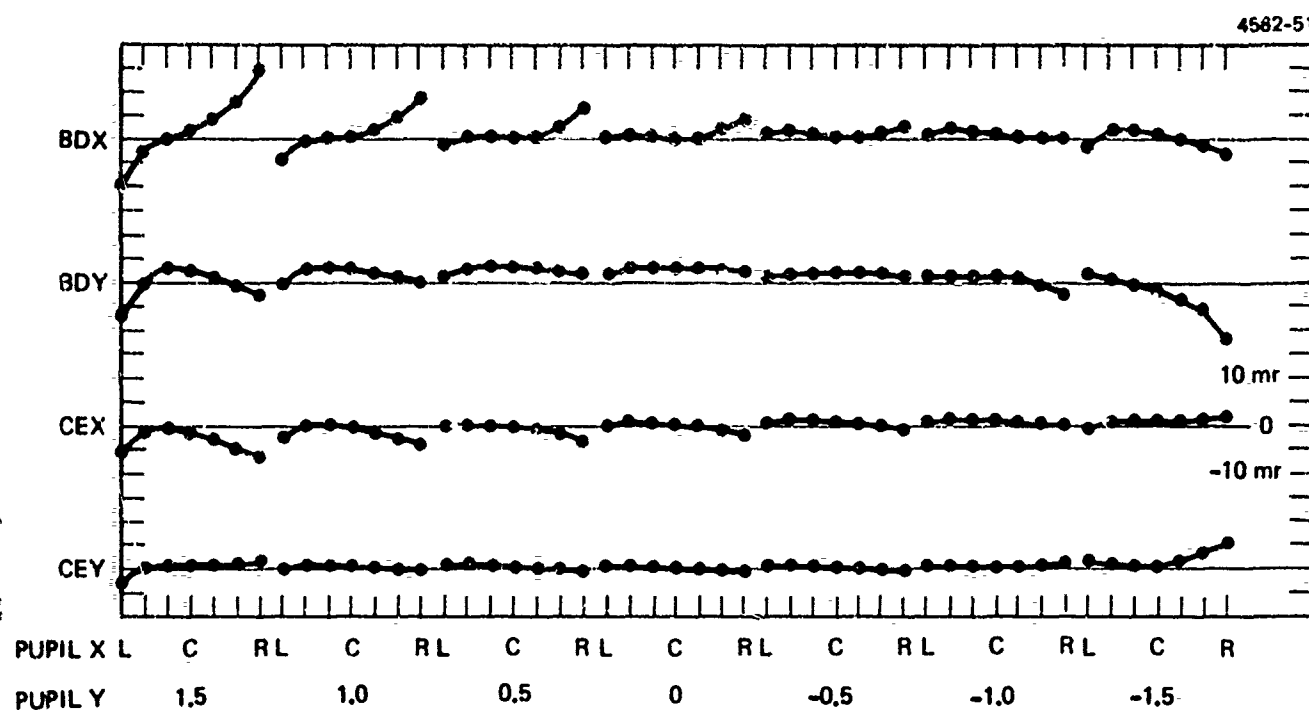


Fig. 35. Binocular disparity (BD) and collimation error (CE) at horizontal field angle of 12.5 degrees.

VII. T90-N8-21.9 Transmission Hologram Lens

1. SYSTEM PARAMETER

T90-N8-21.9 is a 90° off-axis, 8° asymmetric, transmission hologram lens element with a 34.5" eye relief and a 21.9" focal length.

The T90-N8-21.9 is a 90° off-axis, 8° asymmetric, transmission hologram lens element with an eye relief of 34.5" and a focal length of 21.9". The operating wavelength is 632.8 nm. The HUD configuration for which this hologram lens was constructed is shown in Figure 36. The input to the display is the 4" square diffusing screen of the acousto-optical laser scanning system. Imaging is done at an astigmatism minimized intermediate image plane. This imagery will exhibit residual aberrations, because there is no aberration-correcting relay lens optical system.

The hologram aperture is 8" in diameter recorded on Kodak 120-01 silver halide emulsion and bromine bleached.¹⁵ Instantaneous vertical field of view for one eye at the pupil center is $+4.40^\circ$ and -3.65° . Instantaneous horizontal field of view is $\pm 6.61^\circ$. Single binocular vision can be maintained for eyes at the 34.5" eye relief distance. For a nominal 63 mm separated pair of eyes centered at the exit pupil, binocular FOV for each eye is $+4.16^\circ$ and -3.49° vertical, $\pm 4.56^\circ$ horizontal. The relationship of the hologram size to the system parameters is shown in Figure 37.

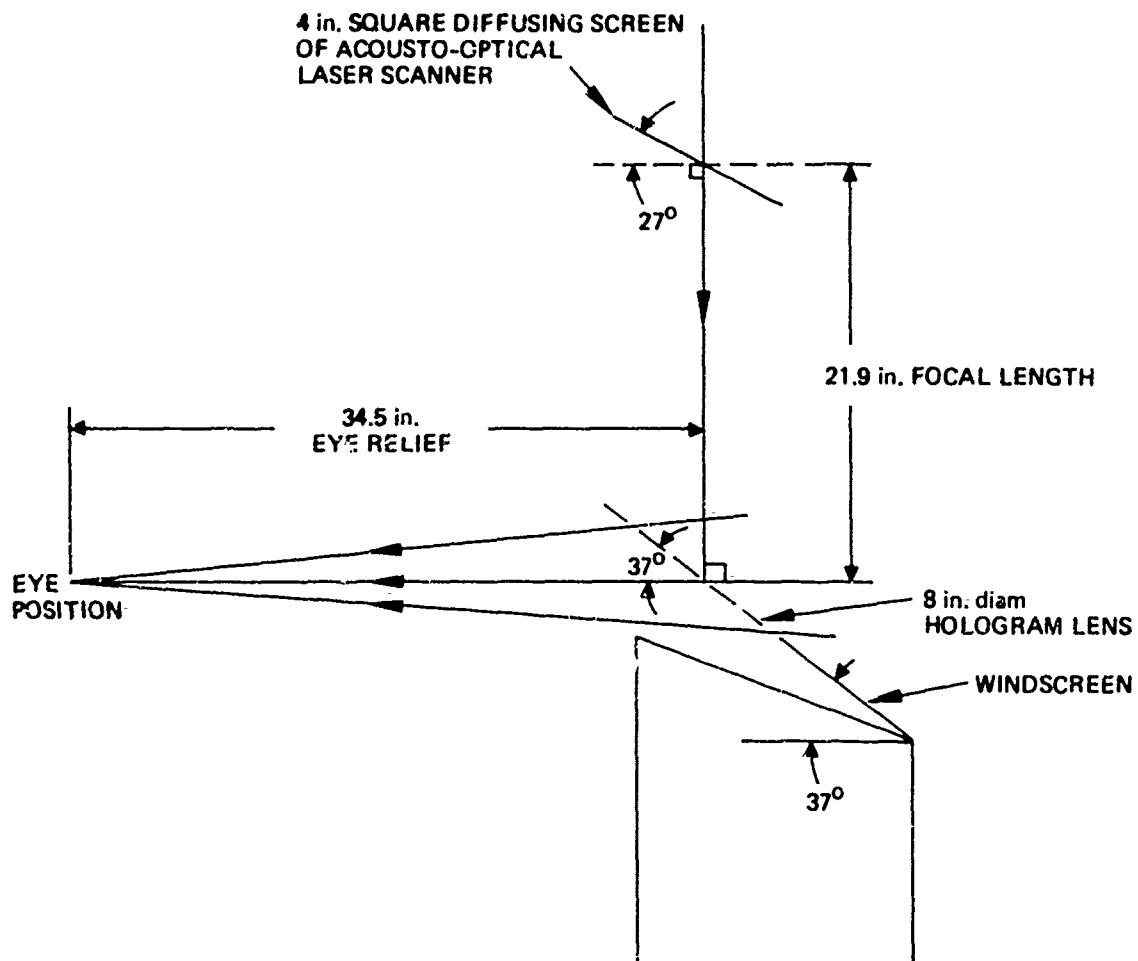


Fig. 36. The T90-N8-21.9 HUD configuration.

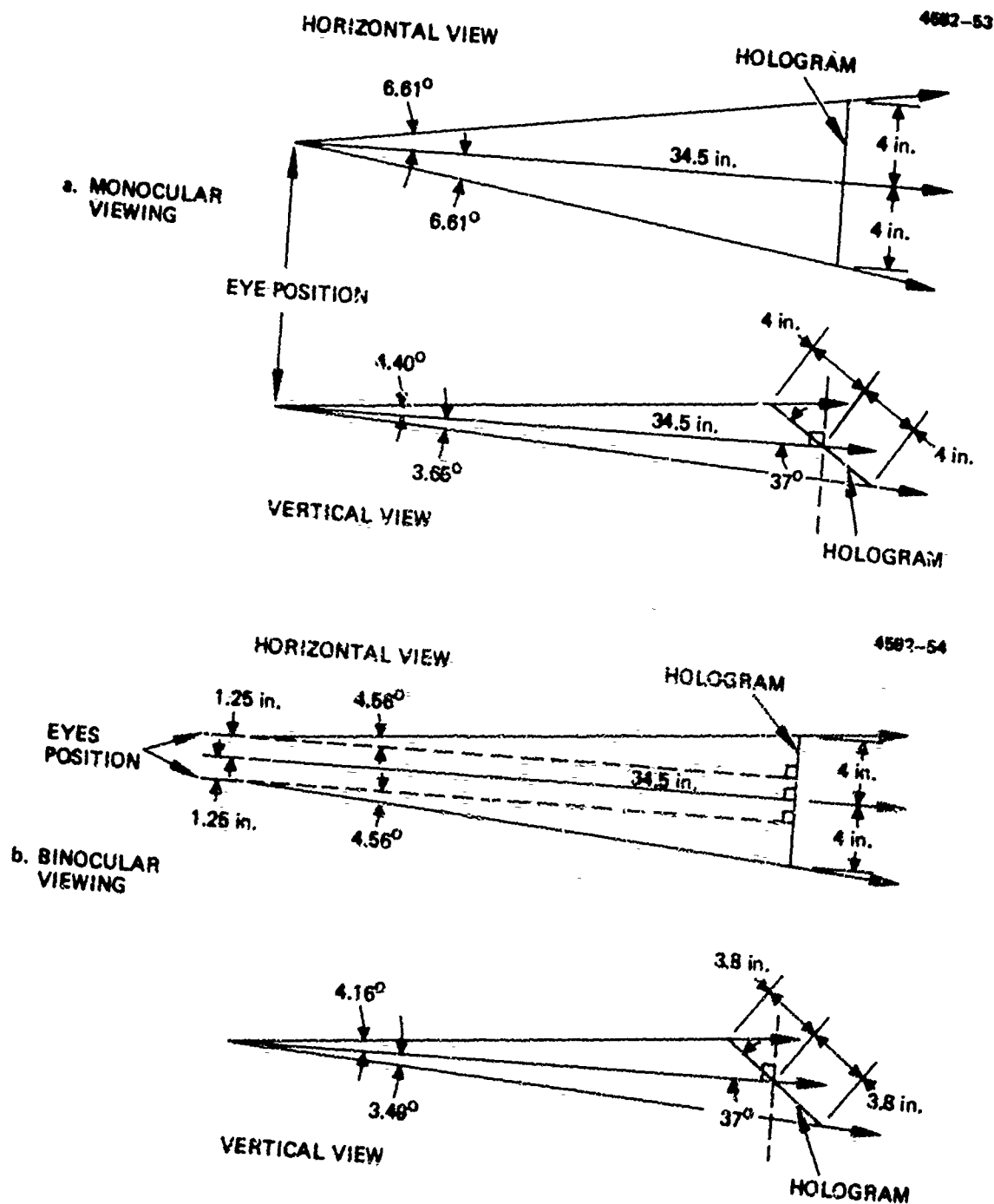


Fig. 37. The relationship of the 8 in. diameter hologram size to the system parameters.

VII. T90-N8-21.9 Transmission Hologram Lens

2. CONSTRUCTION BEAM OPTICAL SYSTEM

The construction beam optical system for the T90-N8-21.9 lens is based on the "continuous lens" concept invented at Hughes Research Laboratories.

The basic "continuous lens" design concept, invented at Hughes Research Laboratories by Gaylord Moss, was used in designing the construction beam optical system for a 90° off-axis, 8° asymmetric transmission hologram lens. However, point source construction beams for asymmetric hologram configurations introduce axial astigmatism as well as a large amount of astigmatism across the field. Computer simulations of the hologram construction and corresponding reconstruction characteristics were made. Axial astigmatism was eliminated with 26.30" of astigmatism in one of the construction beams.

A schematic of the construction system, fabricated to expose the T90-N8-21.9 transmission lens, is shown in Figure 38. Construction optics consist of plane mirrors, spatial filters, beamsplitters, and a 14.38" diameter, 60" radius of curvature spherical mirror. A diverging point source is located 34.5" from the hologram center. The proper amount of astigmatism in the converging construction beam was obtained by using the off-axis aberration of the spherical mirror. The included angle between the construction beams is 90° at the center of the hologram recording plane. The angle between the bisector of this 90° included angle and the hologram recording plane normal is 8° .

The construction system was assembled on a honeycomb optical table supported with pneumatic mounts which dampen floor vibrations. Shielding was provided to minimize atmospheric disturbances. The construction wavelength was the 632.8 nm spectral line from a 50 mw helium-neon laser. Path lengths of the construction beams were matched to the hologram recording plane center.

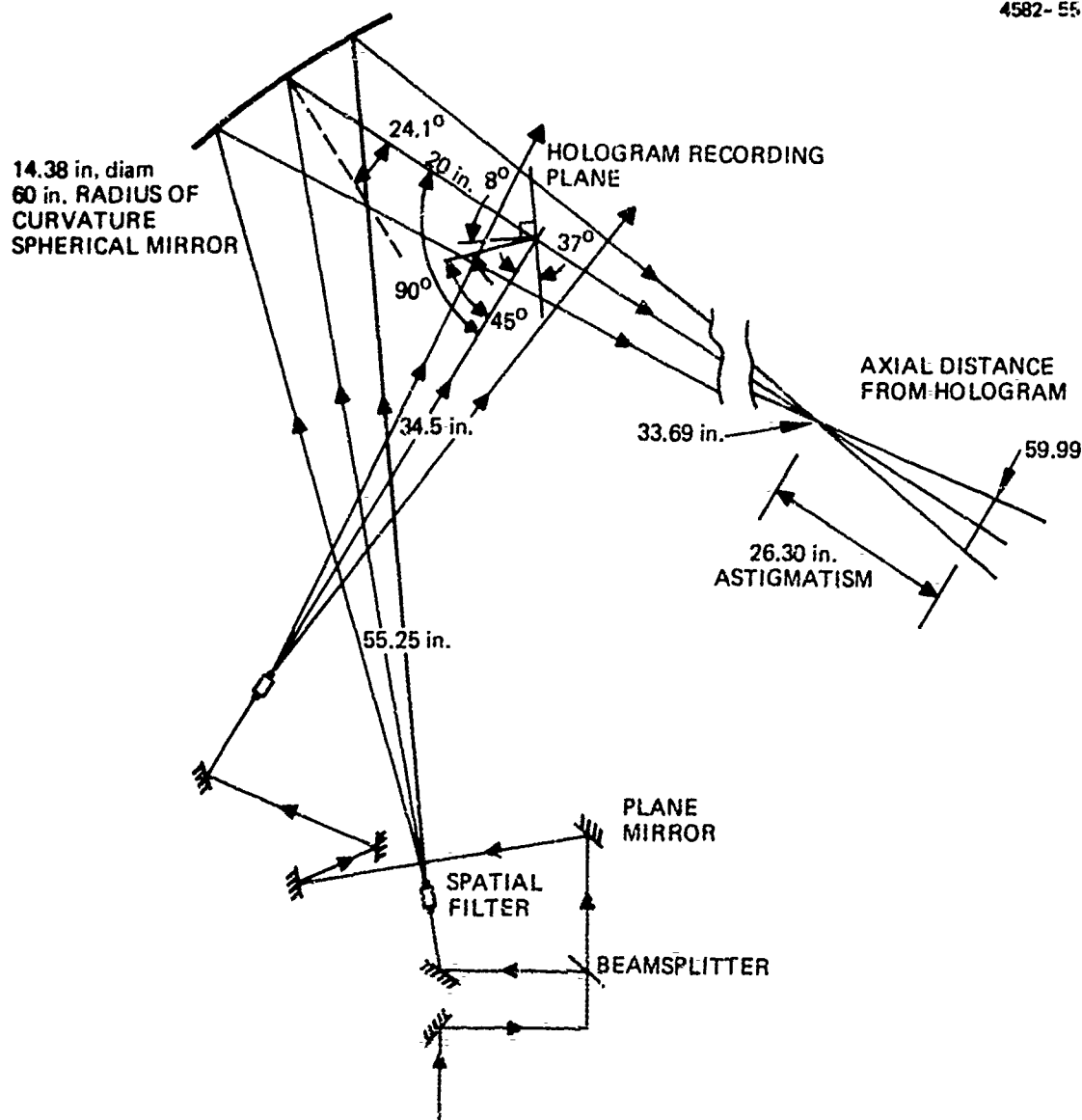


Fig. 38. The construction system for 90° off-axis, 8° asymmetric, transmission hologram lens.

VII. T90-N8-21.9 Transmission Hologram Lens

3. HOLOGRAM LENS FABRICATION

The T90-N8-21.9 hologram lens is exposed on 8" x 10" silver halide emulsion and bromine vapor bleached.

The T90-N8-21.9 transmission hologram lens was recorded on 6- μ m thick, silver halide emulsion (Kodak type 120-01 plates, 8 in. x 10 in.). The resulting amplitude hologram was converted to a phase hologram with bromine vapor bleaching.

A uniform coverage of the 50.27 in.² area of the hologram aperture resulted in recording beams energy of 2.3 μ W/cm² and 2.0 μ W/cm² (measured at the hologram recording plane). An exposure of 65 seconds was required to obtain an exposed energy of 280 μ J/cm². The exposed hologram was processed in 21°C solutions with agitation: 5 minutes in Kodak D-19 developer; 1 minute wash in water; 5 minutes in Kodak fixer with hardener. The processed density of the amplitude hologram was 2.0 ND. The air dried amplitude hologram was then bromine vapor bleached.

Efficiency and scatter was measured at 632.8 nm, the operating wavelength of the bleached silver halide hologram lens. Diffraction efficiency was 11% with 8% scatter. The 8" diameter T90-N8-21.9 hologram lens is sealed (Epotek 310 optical adhesive) on a 1/4" thick glass substrate with dimensions, as specified by NADC shown in Figure 39. This substrate can be mounted in the AIMIS demonstrator to display laser symbology with the hologram lens element.

The efficiency and scatter values are similar to that of the half-scale, 40° off-axis, symmetric transmission lens delivered to NADC in Phase 1 program. There are several probable causes for this low efficiency. The spatial frequency recorded at the center of the T90-N8-21.9 lens is 2218 cycles/mm. The hologram recording plane must be restricted from motion a fraction of 4.50×10^{-7} meter. A major cause of instability was the heat generated by the laser which was positioned on a platform attached to the underside of the honeycomb table. This thermal energy tends to warp the stainless steel surface of the optical table. This type of instability is typically random and cannot be corrected with a fringe stabilizing system of the type developed in Phase 2 program.

Despite the low efficiency, the T90-N8-21.9 transmission hologram lens will adequately display laser symbology in the AIMIS demonstrator. The characteristics of the holographic element are discussed in the next topic. Residual aberration will remain in the imagery due to the absence of an aberration correcting lens system. However, the holographic lens element demonstrates that a complex lens function can be achieved with hologram optics.

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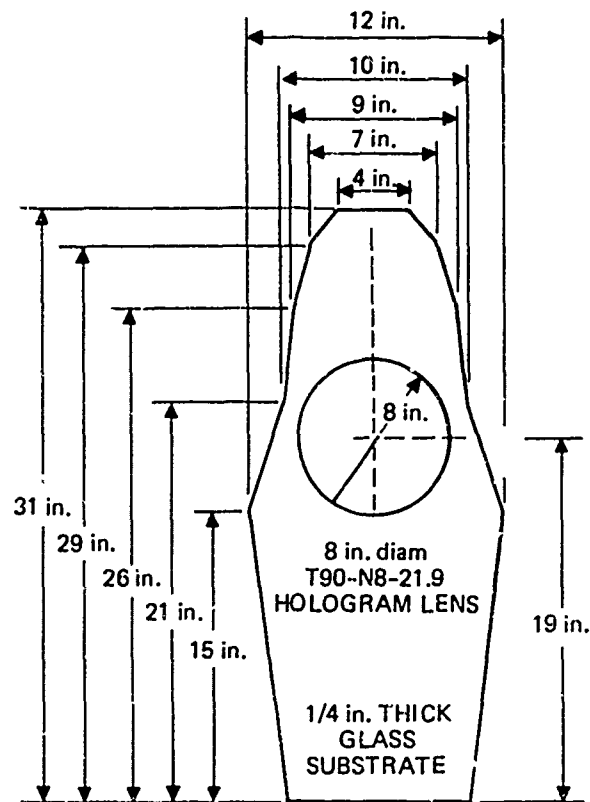


Fig. 39. The T90-N8-21.9 hologram lens is protected between 0.040 in. thick (8 in. x 10 in.) and 0.25 in. thick glass substrates.

VII. T90-N8-21.9 Transmission Hologram Lens

4. INTERMEDIATE IMAGE PLANE AND CHIEF RAY EFFICIENCY

The T90-N8-21.9 hologram lens' image plane has a tilt of 27° from the optical axis normal at a 21.9" focal length.

The T90-N8-21.9 hologram lens' image plane has a 27° tilt from the optical axis normal. The focal length of the element is 21.9 in. The image plane is the bisector plane between the axial tangential planes of the horizontal and vertical spheroidal focal surfaces. Figure 40 shows vertical and horizontal sections of the focal surfaces. The data points, theoretical and experimental, are foci locations of ray traces of collimated chief ray bundle entering the hologram lens at various field angles. A detailed description of the experimental procedure for locating the intermediate image plane can be found in the Test Procedures.¹⁴

The 27° tilted image plane is a plane of best focus for imaging without a relay lens system. Note that there are residual aberrations due to the astigmatism across the field. Relay systems are generally designed to image vertical and horizontal ray fans onto their respective focal surfaces, correcting astigmatism.

However, good projected imagery has been seen in a laboratory set-up with diffused 632.8 nm illumination of photographic slides at the image plane. To display laser symbology with the acousto-optical laser scanner, the 4" square diffusing screen should be located at the intermediate image plane.

The image size for monocular viewing ($+ 4.25^\circ/- 3.50^\circ$ vertical FOV and $\pm 6^\circ$ horizontal FOV) is $+ 1.25"/- 1.13"$ vertical and $\pm 2.31"$ horizontal. For binocular viewing, the vertical FOV is slightly vignetted, $+ 4.16^\circ/- 3.49^\circ$, due to the hologram aperture size. A horizontal image plane dimension of $\pm 1.75"$ is sufficient to allow each eye (63 mm apart) $\pm 4.5^\circ$ FOV. These image plane dimensions are measured directly from data in Figure 40.

Chief ray efficiency was measured as a function of vertical and horizontal field angles, Figure 41. Theoretically, chief ray efficiency should be high due to no angular or wavelength shifts between construction and reconstruction geometry. However, the construction beams were path length matched to the center of the hologram. The degree of coherence and fringe visibility are maximum at this point. Consequently, diffraction efficiency is also maximum. Path length difference between construction rays gradually increase for points away

from the center of the lens. Reduction in coherence and visibility between the construction beams causes chief ray efficiency roll-offs as the field angle increases. By increasing the coherence length of the recording laser source, an improvement in chief ray uniformity can be expected.

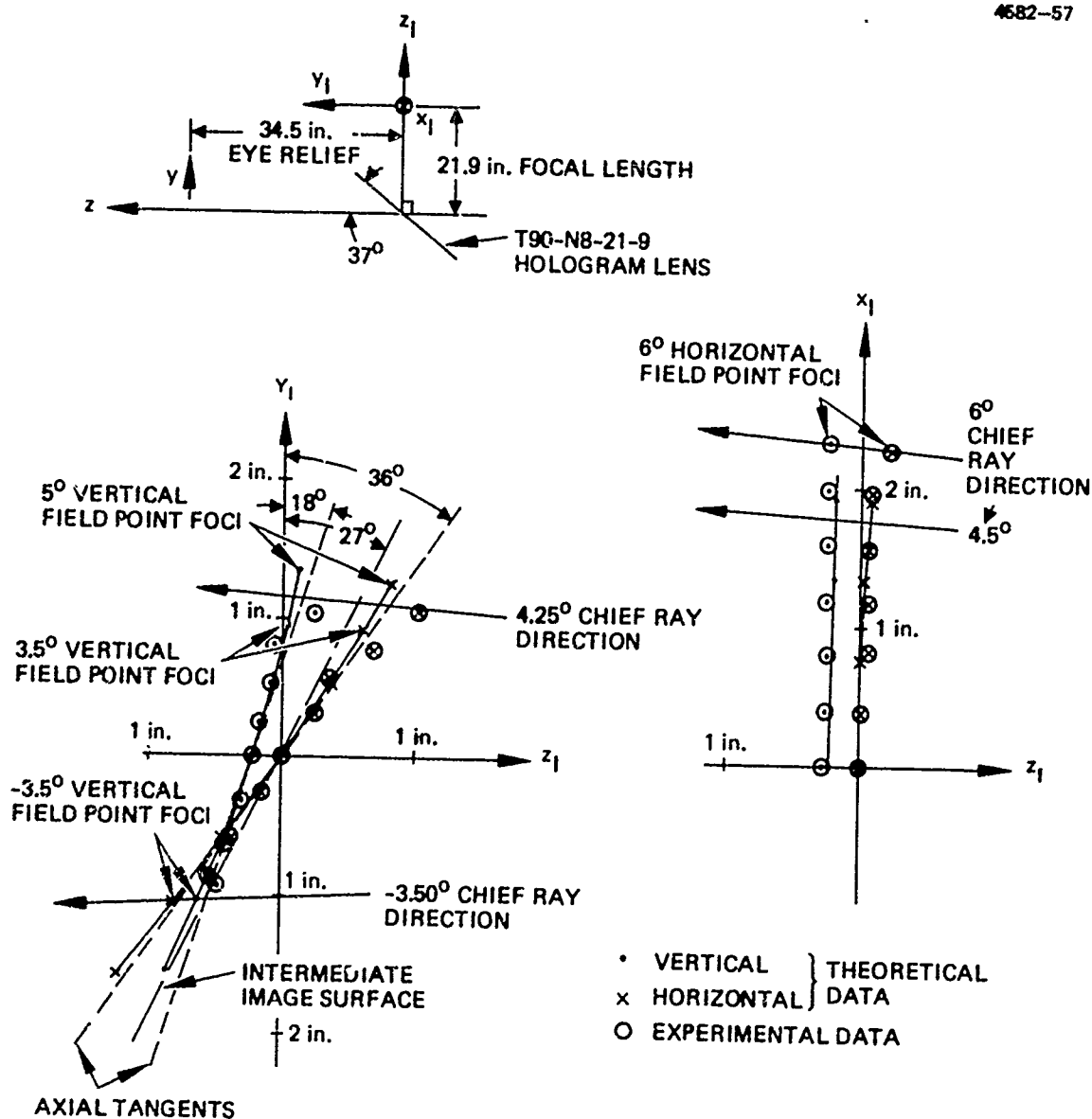


Fig. 40. Vertical and horizontal sections of the spheroidal image (focal) surfaces of the T90-N8-21.9 hologram lens.

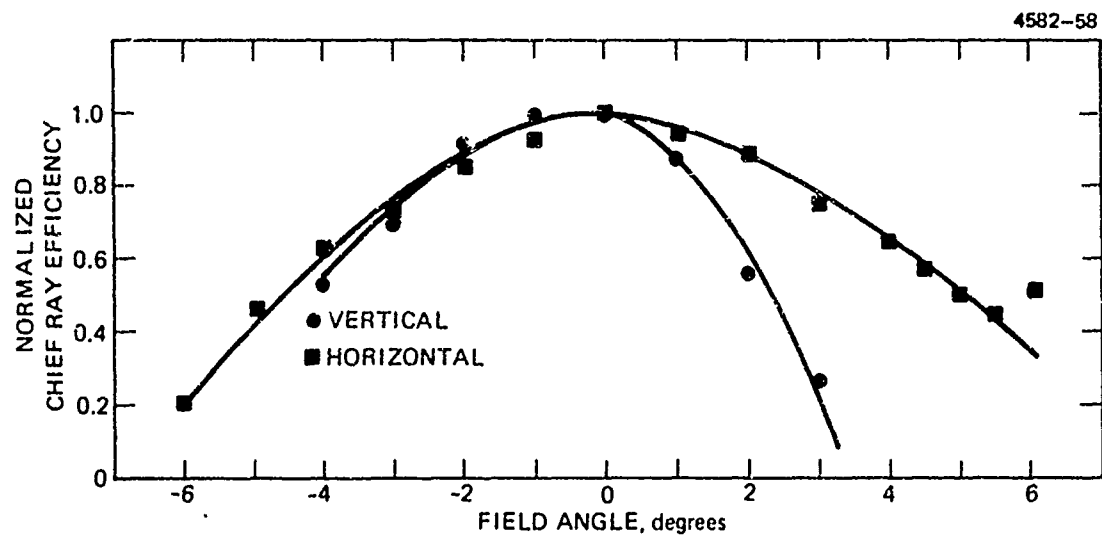


Fig. 41. Chief ray efficiency measured as a function of vertical and horizontal field angles.

REFERENCES

1. "Specification of Hologram Lens System," Naval Air Development Center, Air Vehicle Technology Department, 20 November 1972.
2. Final Technical Report for period 2 April 1973 - 1 April 1974, Contract N62269-73-C-0388, "Holographic Lens for Pilot's Head-Up Display," prepared for Naval Air Development Center, Warminster, PA 18974, by Hughes Research Laboratories, Malibu, CA 90265, D.H. Close, A. Au, and A. Graube, August 1974.
3. Final Technical Report for period 1 July 1974 - 31 October 1974, Contract N62269-74-C-0642, "Holographic Lens for Pilot's Head-Up Display," prepared for Naval Air Development Center, Warminster, PA 18974, by Hughes Research Laboratories, Malibu, CA 90265, D.H. Close, A. Au, and A. Graube, 1 April 1975.
4. G.E. Moss, "Wide-Angle Holographic Lens for a Display System," J. Opt. Soc. Am. 64, 552A, April 1974.
5. R.J. Collier, C.B. Burckhardt, and A.H. Lin, Optical Holography (Academic Press, New York, 1971).
6. A. Graube, Opt. Comm. 8, 251-253 (1973).
7. M. Chang, Appl. Opt. 10, 2550-2551 (1971).
8. J.E. Jolley, Photographic Science and Engineering 14, 169-177, (1970).
9. W.S. Colburn, R.G. Zech, and L.M. Ralston, "Holographic Optical Elements," Harris Electro-Optics Center of Radiation, Technical Report AFAL-TR-72-409 (1973).
10. W.S. Colburn and B.J. Chang, "Design and Fabrication of Hologram Optical Elements," Final Technical Report AFAL-TR-74-281, Environmental Research Institution of Michigan (1975).
11. T.P. Sosnowski and H. Kogelnik, Appl. Optics 9, 2186-2187 (1970).
12. D.H. Close and A. Graube, "Material for Holographic Optical Elements," Technical Report AFML-TR-73-267, Hughes Research Laboratories (1973).

13. R.D. Anwyl, Eastman Kodak Company, private communication.
14. Test Procedures for Contract N62269-75-C-0299, "Holographic Lens for Pilot's Head-Up Display," prepared for Naval Air Development Center, Warminster, PA 18974, by Hughes Research Laboratories, Malibu, CA 90265, A. Au, October 1975.
15. A. Graube, Appl. Opt. 13, 2942-2946 (1974).