Holography

Purpose

The goal of this experiment is to learn the basics of holography by making a two-beam transmission hologram.

Introduction

A conventional photograph registers a scene as a two dimensional distribution of light intensity recorded on a piece of film at the image plane of a camera lens. The three-dimensional character of the original scene, as perceived through parallax and focal depth, is lost in the film image. Parallax refers to the change in perspective that occurs as the viewing angle is changed, and focal depth refers to the need to refocus the eyes as portions of the scene at different distances are examined. Information is lost in the photograph because the film records only the light intensity, but not the phase information that would be necessary to reconstruct the original wave fronts.

The three dimensional character of the scene could be restored if one could reconstruct the detailed wave fronts emitted from the original scene. Amazingly, the method of holography, first proposed by Gabor in 1948, accomplishes just this.

A hologram is a direct record on film of the interference fringes formed by superposing a coherent reference beam on the light scattered from an illuminated object. The camera lens is eliminated. Fully three-dimensional images are reconstructed by illuminating the film in its original position by the coherent reference beam alone. The fringes on the film behave as a grating that diffracts the incident light from the reference beam, giving rise to several images from the various orders of diffraction.

Scientific applications of holography are widespread, along with applications in art and entertainment. Especially important are techniques of holographic interferometry, pattern recognition and storage, and image processing. There are several methods for producing real-time holographic motion pictures, which have important applications in the analysis of mechanical vibrations and other small motions.

References

1. Welford Chapter 7
2. Heavens and Ditchburn, Chapter 13 (available in the lab)
3. Reynolds, DeVelis, Parrent, & Thompson, Chapters 25, 26 & 27
4. G. Saxby, *Practical Holography*

Problem Set #6

1. See Fig. 6.1 below. Suppose that L_1 is a 60x microscope objective and the distance from the focal point P_R to the film plane is 40 cm. How long should the shutter be left open for proper exposure of the film? See the section below on properties of the LitiHolo self-developing holography plates.
2. See Fig 6.2 below. Suppose the reference beam point source P_R has (y,z) coordinates (0,-40 cm) and a point P_O on the object has coordinates (-10cm, -15cm). Where are the orthoscopic and pseudoscopic images located? Which images are real and which virtual?

Holography Apparatus

A typical set-up for writing dual beam holographs is shown in Fig 6.1. The laser beam is divided into two mutually coherent beams by the beam splitter **BS**. The reflected beam is steered by mirror, $\mathbf{M_1}$, then expanded by lens $\mathbf{L_1}$ to create a divergent spherical wave that serves as the reference beam. This beam must illuminate the entire area of the film **H**.

The beam transmitted by the beam splitter is reflected by mirror $\mathbf{M_2}$, and then expanded by microscope lens $\mathbf{L_2}$ to form the illumination beam. The geometry must be chosen so that the illumination beam fully illuminates the side of the object **O** that faces the film. Light scattered by **O** interferes with the reference beam to produce the fringes that are recorded by the film **H**. When the film is developed the fringes appear as a pattern of fine dark lines, which may be examined with a microscope. Many variations on the geometry are possible. The reference and illumination beams must be expanded to a area large enough to illuminate the entire film/object—typically a 60x objective are needed to expand a He-Ne beam. The distance from the beam splitter to each mirror is in the neighborhood of 16 cm, and the distance from $\mathbf{P_R}$ to the film plane is about 40 cm. The object can be placed on either side of the reference beam (above or below, referring to Fig 6.1). Not shown in the figure are the shutters that control the film exposure time.

To reconstruct the image, the developed film should be placed in a film holder at location **H**, the same location where it was exposed. The illumination beam is then blocked by a beam stop placed between **BS** and $\mathbf{M_2}$, and the original object is removed. The fringes in the hologram now serve as a diffraction grating, which splits the reference beam into several distinct images. One order of diffraction produces a virtual image at the position of the original object. This **orthoscopic** image, which possesses the same three-dimensional character as the original scene, may be viewed by looking through the film towards the object position. Another image, called the pseudoscopic image can also be seen in most cases. The location and magnification of this image depends on the details of the geometry. If the pseudoscopic image is real it may be observed by placing a screen in front of the hologram.

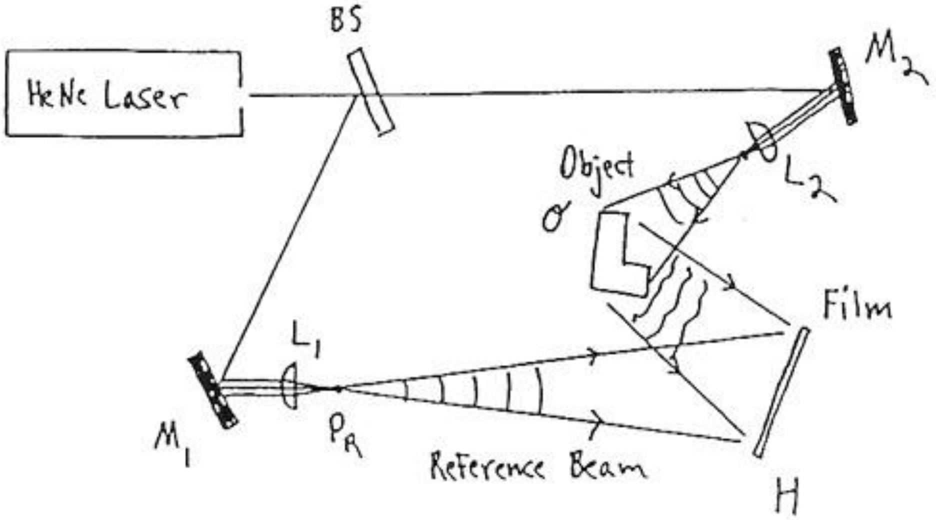


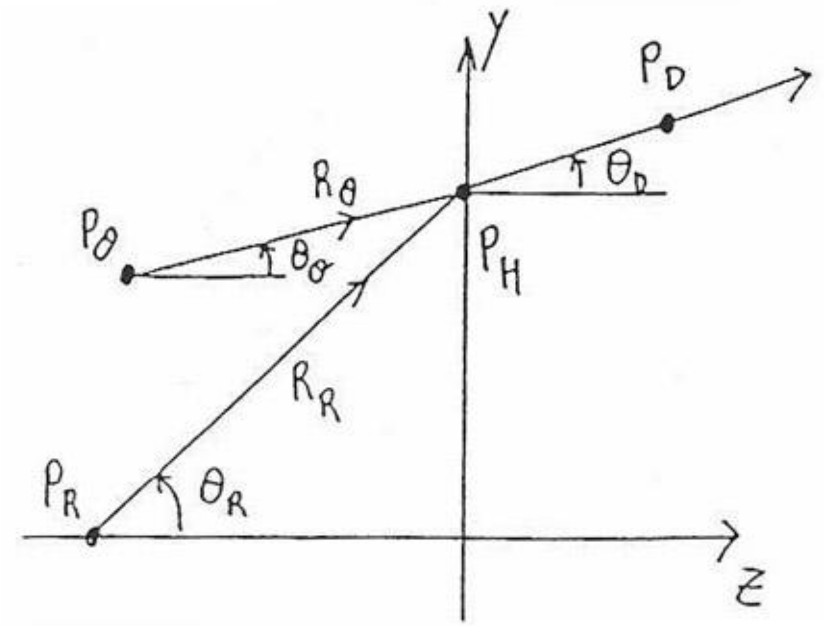
Fig 6.1 Dual-beam Transmission Holography Apparatus

The useful coherence length of the HeNe lasers in our lab is in the neighborhood of 5 cm to 25 cm. The older, lower power lasers tend to have longer coherence lengths because they operate closer to threshold, and fewer off-center modes are excited. To be sure that the two beams form an interference pattern at the film plane **H**, the optical path difference along the two paths from the beam splitter the film plane **must** be less than the coherence length of the laser. To be safe you should aim for a path length difference in your setup of at most 1-2 centimeters. The path length difference can be adjusted by moving mirror $\mathbf{M_1}$.

Holograms are very vibration sensitive—very small motions of the apparatus can shift the fringes on the film, totally washing-out the hologram. Thus, it is important that the optics are very solidly mounted. Furthermore, even the action of the shutter in the camera back can cause fatal vibrations. Thus, the best procedure is to open the camera shutter **while blocking the camera entrance with an opaque card, that you are holding** while being careful not to touch the table. Then make the exposure "manually," moving the card away while counting exposure, then moving the card back in the way. Then close the camera shutter. In this way, you can keep the apparatus as vibration free as possible while doing the exposure. Take a number of progressively longer exposures on one film strip, to increase your chances of obtaining an image with the appropriate exposure.

Holographic image formation and reconstruction

In this section we give a simple theory for the formation and reconstruction of holographic images. The theory is sufficient to predict the location and type of images that will be visible where the hologram is reconstructed. Our geometry is shown in Fig 6.2. Instead of dealing with the complexity of an extended object, we consider only a point source on the object at the point **$P_{0,}$**, which emits spherical waves that are coherent with the reference beam. The reference beam consists of spherical waves emitted from the point **P_R**. We fix the y-coordinate of **P_R** to be zero. Normally the z-coordinate of **P_0** and **P_R** would both be negative numbers (i.e. in the left-hand side of the plane), but the y-coordinate of **P_0** may be either positive or negative. The film is located in the plane z=0, and **P_H** is a point on the film plane. When the image is reconstructed there will be a diffracted ray leaving **P_H** at the angle θ_D(measure from the positive z-axis). **P_D** labels a point on the diffracted ray.



Point	Coordinates
P_R	$(0, z_R)$
$P_{\square}$	(y_O, z_O)
P_H	$(y_H, 0)$
P_D	(y_D, z_D)

Fig 6.2 Geometry for Theory of Two-beam Hologram

Our first task is to find the fringe spacing $\Lambda(y_H)$ on the hologram. The superposed electric fields from the object and the reference beam have the form

$$E = E_O e^{i(kR_O - wt)} + E_R e^{i(kR_R - wt)}$$

on the film plane. The film records the intensity (time averaged)

$$\mathrm{I} \propto \overline{\left(\mathrm{Re}\left(E\right)\right)^2} = \frac{1}{2}(E_O^2 + E_R^2 + 2E_O E_R \cos k(R_O - R_R)),$$

which contains the crucial $\cos[k(R_O - R_R)]$ interference term. (The wave number k is equal to $2\pi/\lambda$.) When moving along the film plane we will move from one interference maximum to the next when the path length difference R_O-R_R changes by one wavelength λ.

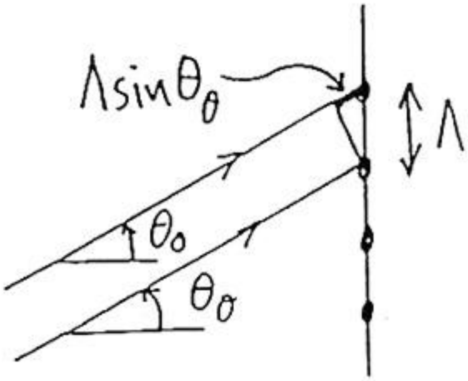


Fig 6.3

Fig. 6.3 shows that the path length from the object point $\mathbf{P_O}$ to the film changes by $\Lambda\sin\theta_O$ from one fringe to the next. Similarly, the path length from the reference beam source P_R to the film changes by $\Lambda\sin\theta_R$ from one fringe to the next. Thus the fringe spacing Λ is fixed by the condition

$$|\Lambda\sin\theta_R - \Lambda\sin\theta_O| = \lambda,$$

or

$$\Lambda = \frac{\lambda}{|\sin\theta_R - \sin\theta_O|}$$

Next we will use the fringe spacing formula to find the direction of the diffracted rays θ_D when the hologram is illuminated only by the reference beam. Fig 6.4 shows the path lengths along rays going through adjacent fringes of the hologram. The condition for constructive interference is

$$\Lambda\sin\theta_D - \Lambda\sin\theta_R = n\lambda$$

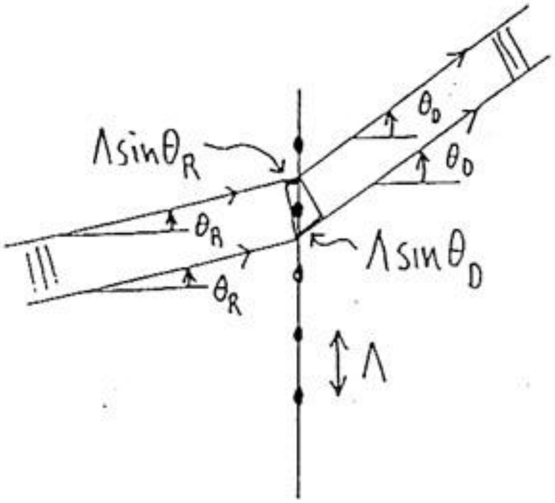


Fig 6.4

Combining this result with the formula for the fringe spacing yields an equation for the diffraction angle $\boldsymbol{\theta_D}$:

$$\boxed{\sin\theta_D = (n+1)\sin\theta_R - n\sin\theta_O} \qquad \textbf{(1)}$$

This is the fundamental result describing two-beam transmission holography. For **n**=0 we have

$$\sin\theta_D = \sin\theta_R$$

which says that the zero-order diffracted beam is simply the undeflected reference beam. For **n**=1 we get the more interesting result

$$\sin\theta_D = \sin\theta_O$$

This means there will be diffracted rays that appear to come from the original position of the object $\mathbf{P_0}$. Thus there is a virtual image at the original object location. This is called the orthoscopic image.

For other values of **n** the position of the image can only be found by further analysis. To keep things reasonably simple we will now restrict ourselves to the paraxial approximation for which $\boldsymbol{\theta_D}$, $\boldsymbol{\theta_R}$, $\boldsymbol{\theta_O}$, are all much less than one. The angles are then related to the coordinates of the points $\mathbf{P_D}$, $\mathbf{P_H}$, $\mathbf{P_0}$, and $\mathbf{P_R}$ by

$$\theta_D = \frac{y_D - y_H}{z_D}, \theta_R = \frac{y_H}{-z_R}, \theta_O = \frac{y_H - y_O}{-z_O}$$

Using these expressions and the small angle approximation in Eqn. 1 gives

$$\frac{y_D - y_H}{z_D} = -(n+1)\frac{y_H}{z_R} + n\frac{y_n - y_O}{z_O},$$

which may be solved for $\mathbf{y_D}$ to yield

$$y_D = (-(n+1)\frac{z_D}{z_R} + n\frac{z_D}{z_R} + 1)y_H - n\frac{z_D}{z_O}y_O$$

The image point with coordinates (**y_D'- z_D'**) is that point on the diffracted ray where **y_D(z_D)** is independent of **y_H**. This occurs when

$$-(n+1)\frac{z_D'}{z_R} + n\frac{z_D'}{z_O} + 1 = 0,$$

or at the coordinates

$$\boxed{\frac{1}{z_D'} = \frac{(n+1)}{z_R} - \frac{n}{z_O}\,,\ y_D' = n\frac{z_D'}{z_O}y_O} \qquad \textbf{(2)}$$

Eqn. 2 may be used to reproduce the previous results for **n**=0 and **n**=-1 diffraction. The case **n**=+1 is called the pseudoscopic or conjugate image, and Eqn. 2 shows that it may be either real or virtual (**z_D'** may be either positive or negative) depending on whether **z_R** is greater than or less than 2 **z_O**.

Self-developing Litiholo Holography Plates

To create a hologram, the interference pattern created by the reference and scattered beams must be recorded in some material that allows you to later use a single beam (the reference beam) to recreate the scattered beam, and thereby view the holographic image. Presently, we are using ‘self-developing’ holography plates from Litiholo (see their website at http://www.litiholo.com). The plates carry a layer that changes upon exposure to red light, so that it causes an optical phase shift that is different in the exposed regions than in the unexposed regions. See the references for more information about how this process works. In any case, **the full change in the plate requires exposure to roughly 60 mJ/cm^2 of red light**.

The most common reason for failing to record a good hologram is vibrational smearing of the interference pattern, so be careful of vibrations. However, the second most common reason is that your Litiholo plate has been underexposed. The third most common problem is that the Litiholo plates have a finite shelf life, measured in months, and you’ve somehow gotten an old plate. We resupply these plates each term, so it should not be a problem, but be aware that plates cannot be exposed to room light without degrading. After all, some of the room light is red.

For your further amusement, we include below the data sheet for Kodak SO-253 holography film, an obsolete and no longer available product, which we used to use in the lab. It required development after the recording of the hologram and was quite touchy.

KODAK High Speed Holographic Film SO-253 (ESTAR Base)

and

KODAK Special Plates, Types 131-01 and 131-02

DESCRIPTION & APPLICATION

This new film provides extraordinary speed when exposed with helium-neon (633 nm) or krypton (647 nm) lasers. At the same time, its microfine grain structure and other emulsion characteristics combine to yield high diffraction efficiency and low noise upon reconstruction of holograms recorded at spatial frequencies as high as 1500 cycles/mm. It is recommended primarily for holographic interferometry and micrography, and it is particularly useful for general holographic procedures with low-power HeNe lasers.

The film can also be exposed efficiently with helium-cadmium (442 nm), argon (515 nm), and frequency-doubled Nd:YAG (532 nm) lasers. At these wavelengths, film speed is at a level to be expected from materials having the grain size and resolving power of SO-253 Film; it is low only by comparison with the inordinately high sensitivity achieved in the 600-660 nm region. (Some reduction in holographic performance is to be expected at progressively shorter wavelengths a a result of Rayleigh scattering in the emulsion during exposure, but this is characteristic of all silver-halide holographic materials.)

The emulsion is coated 9 µm thick on a clear 4-mil (100 µm) ESTAR polyester support. A dyed gelatin pelloid on the base side provides antihalation protection and permits convenient handling in both roll and small sheet or short strip formats.

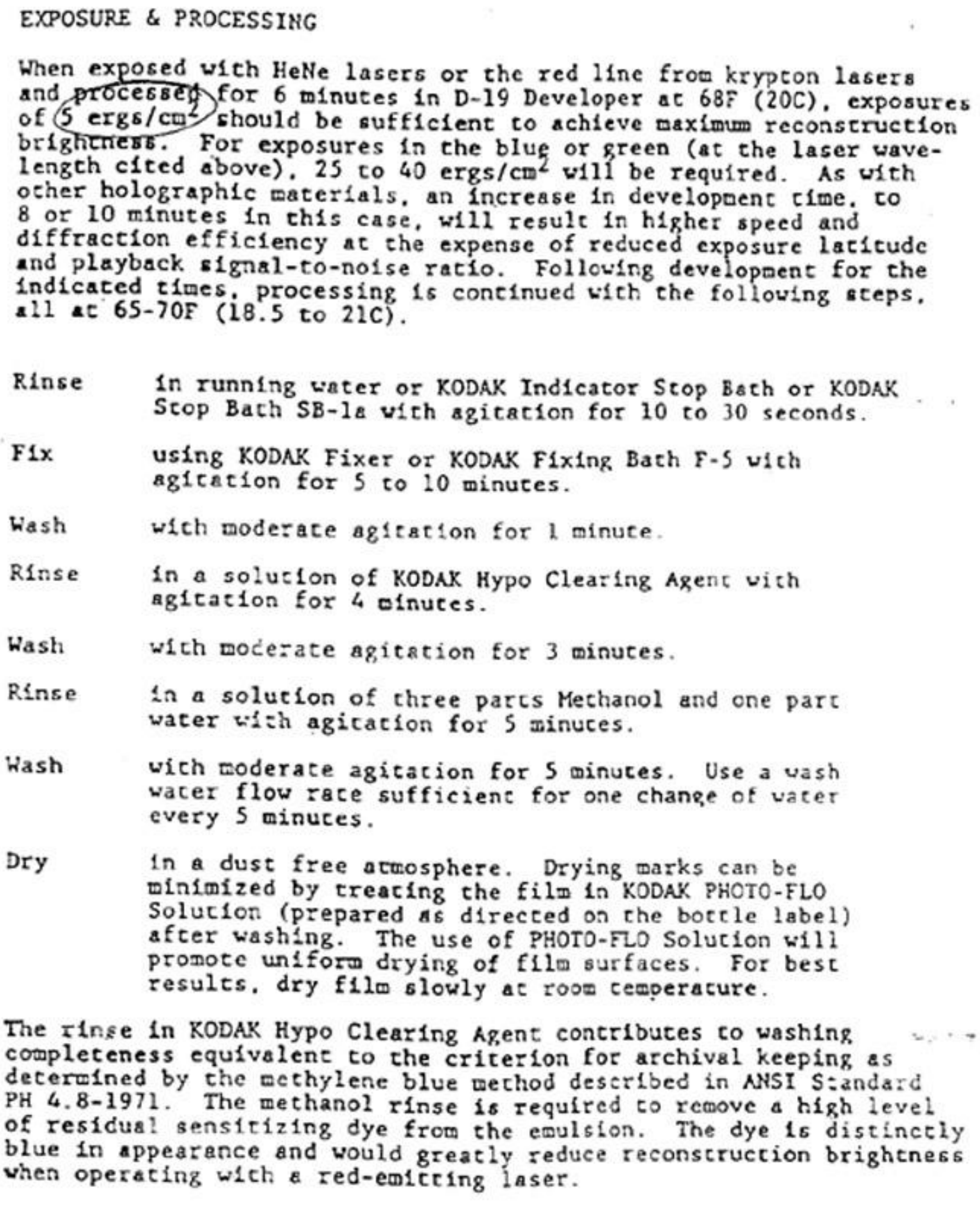
IMAGE STRUCTURE DATA

The following data are based on exposure to tungsten illumination with a KODAK WRATTEN Filter, No. 29 (Deep Red) and processing in KODAK Developer D-19 for 5 minutes at 68F (20C) with continuous agitation.

RMS Granularity:	5	with 48 µm aperture diameter
	14	with 6 µm aperture diameter
		read at a net diffuse visual density of 1.0

Resolving Power:	T.O.C.	1000:1	1250 lines/mm
		1.6:1	800 lines/mm

These values for resolving power were determined by classical (non-holographic) means. They should not be interpreted as limits o holographic resolving power, for which no standard test method or widely accepted criterion exists. For exposures at 633 or 647 nm, SO-253 Film should reconstruct holograms recorded at frequencies exceeding 1500 fringes/mm, corresponding to an angular beam separation of approximately 60°



EXPOSURE & PROCESSING

When exposed with HeNe lasers or the red line from krypton lasers and processed for 6 minutes in D-19 Developer at 68F (20C), exposures of 5 ergs/cm^2 should be sufficient to achieve maximum reconstruction brightness. For exposures in the blue or green (at the laser wavelength cited above), 25 to 40 ergs/cm^2 will be required. As with other holographic materials, an increase in development time, to 8 or 10 minutes in this case, will result in higher speed and diffraction efficiency at the expense of reduced exposure latitude and playback signal-to-noise ratio. Following development for the indicated times, processing is continued with the following steps, all at 65-70F (18.5 to 21C).

Rinse	in running water or KODAK Indicator Stop Bath or KODAK Stop Bath SB-1a with agitation for 10 to 30 seconds.
Fix	using KODAK Fixer or KODAK Fixing Bath F-5 with agitation for 5 to 10 minutes.
Wash	with moderate agitation for 1 minute.
Rinse	in a solution of KODAK Hypo Clearing Agent with agitation for 4 minutes.
Wash	with moderate agitation for 3 minutes.
Rinse	in a solution of three parts Methanol and one part water with agitation for 5 minutes.
Wash	with moderate agitation for 5 minutes. Use a wash water flow rate sufficient for one change of water every 5 minutes.
Dry	in a dust free atmosphere. Drying marks can be minimized by treating the film in KODAK PHOTO-FLO Solution (prepared as directed on the bottle label) after washing. The use of PHOTO-FLO Solution will promote uniform drying of film surfaces. For best results, dry film slowly at room temperature.

The rinse in KODAK Hypo Clearing Agent contributes to washing completeness equivalent to the criterion for archival keeping as determined by the methylene blue method described in ANSI Standard PH 4.8-1971. The methanol rinse is required to remove a high level of residual sensitizing dye from the emulsion. The dye is distinctly blue in appearance and would greatly reduce reconstruction brightness when operating with a red-emitting laser.

RECIPROCITY ADJUSTMENTS

Over the range from 1 to 10^{-4} secs, this film shows virtually no reciprocity effects. Data for shorter times are not available. For exposure durations of 10 to 100 seconds, exposures should be approximately 25% greater than those calculated from trial exposures of 1 second or less duration.

LATENT IMAGE DECAY

Like most films with extremely fine grains, SO-253 Film exhibits significant latent image fading during the hours just following exposure. For example, an exposure sufficient to yield a density of 1.0 when the film is processed immediately, will result in a density of 0.8 if processing is deferred for one hour. It is good practice in determining an optimum exposure level for a given holographic setup to process as soon after exposure as possible, provided that the elapsed time can be maintained for all subsequent operations with the same setup.

STORAGE

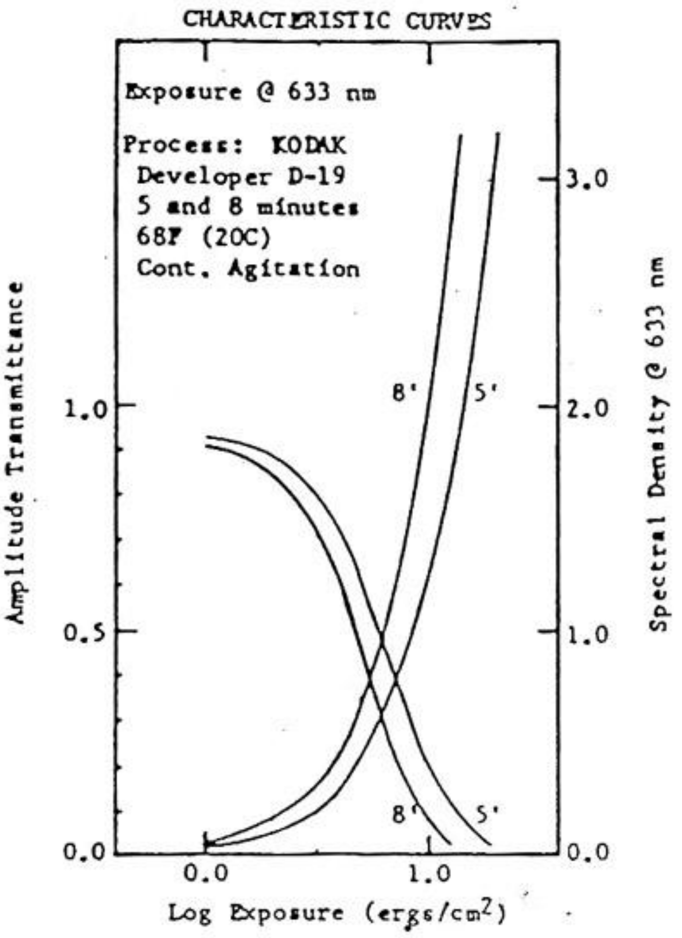
Unexposed film should be stored in a cool place (70F or lower) in the original sealed package. If stored in a refrigerator, remove about 2 hours before opening to prevent condensation of atmospheric moisture on cold film. Otherwise, spotting, ferrotyping, or sticking may occur. In addition, thermal expansion during exposure will result in smearing of holographic fringes. Freezing of the film is not required to assure long shelf life.

SAFELIGHT RECOMMENDATIONS

Total darkness is recommended when handling this film. Indeed, its unusually high red sensitivity will generally require greater care in shielding the film from laser radiation extraneous to the actual holographic exposure than you may be accustomed to providing with materials previously available. Green-fluorescing safety markers or green safelights at very subdued levels may be tolerable in the holographic laboratory or photographic darkroom, but they should be used only after practical film-fogging tests indicate no discernible increase in minimum film density after normal processing.

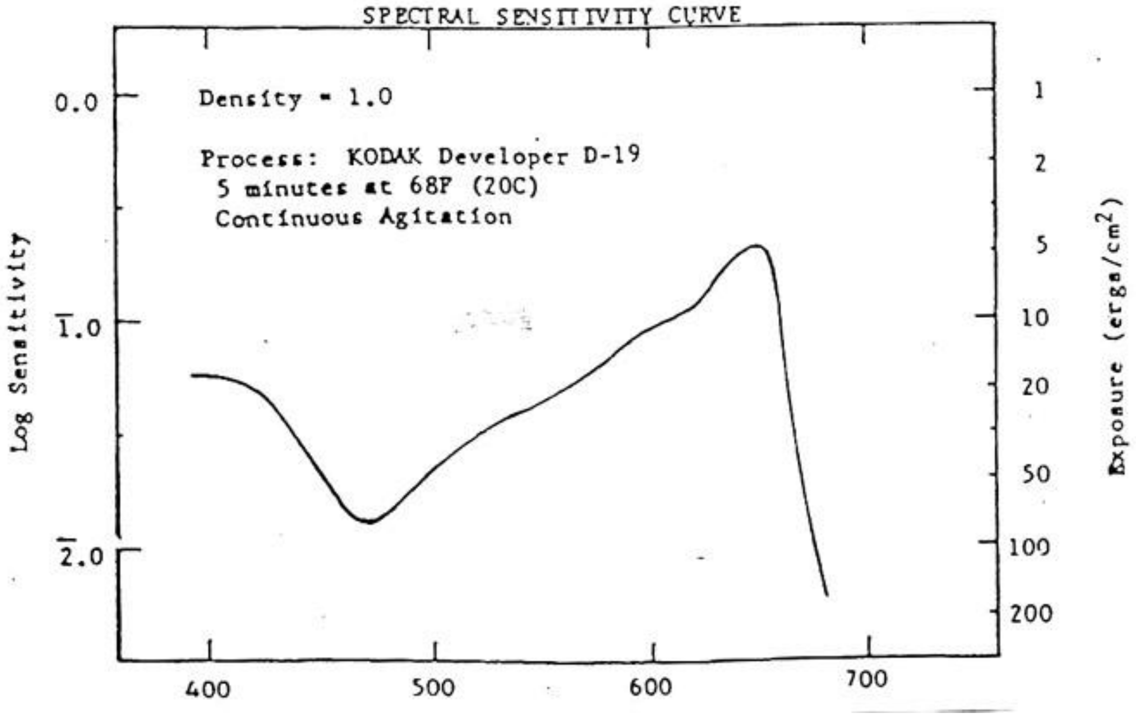
Scientific Photography Markets

EASTMAN KODAK COMPANY - ROCHESTER, NEW YORK 14650



KODAK High Speed Holographic Film (ESTAR Base) SO-253

The sensitometric curves and data in this publication represent product tested under the conditions of exposure and processing specified. They are representative of production coatings and, therefore, do not apply directly to a particular box or roll of photographic material. They do not represent standards or specifications which must be met by Eastman Kodak Company. The Company reserves the right to change and improve product characteristics at any time.



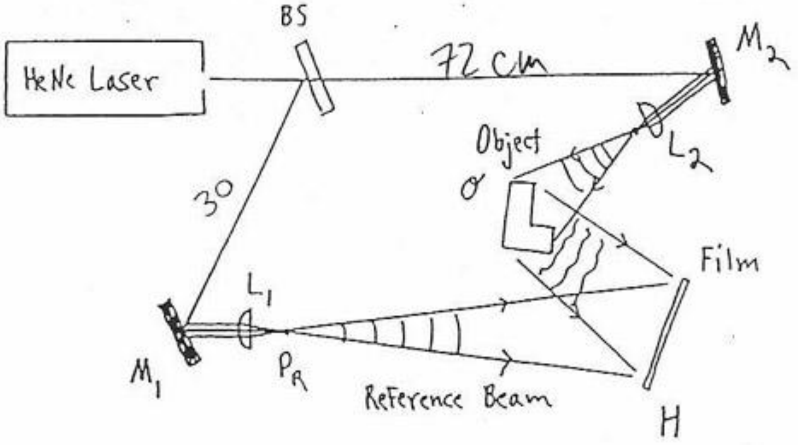
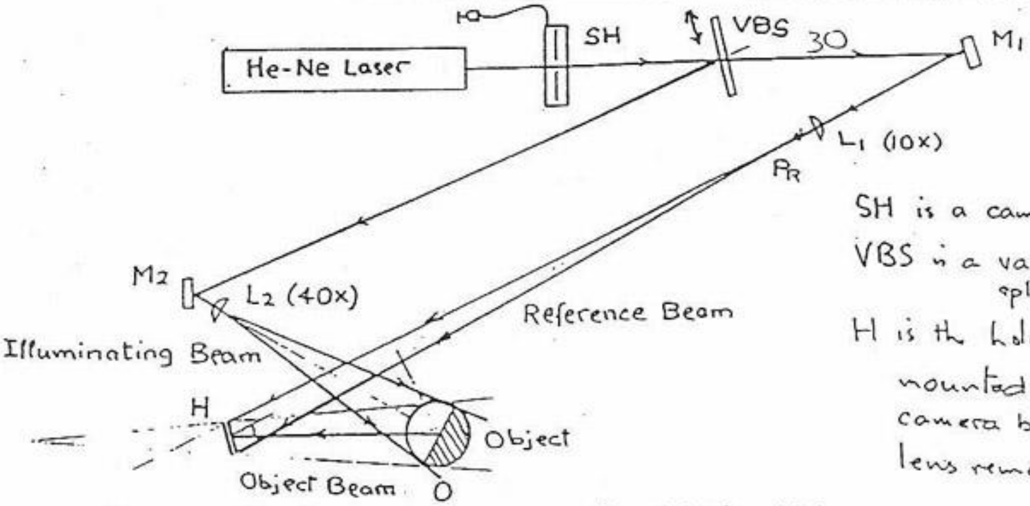


Figure 6.1 Dual-beam Transmission Holography Apparatus

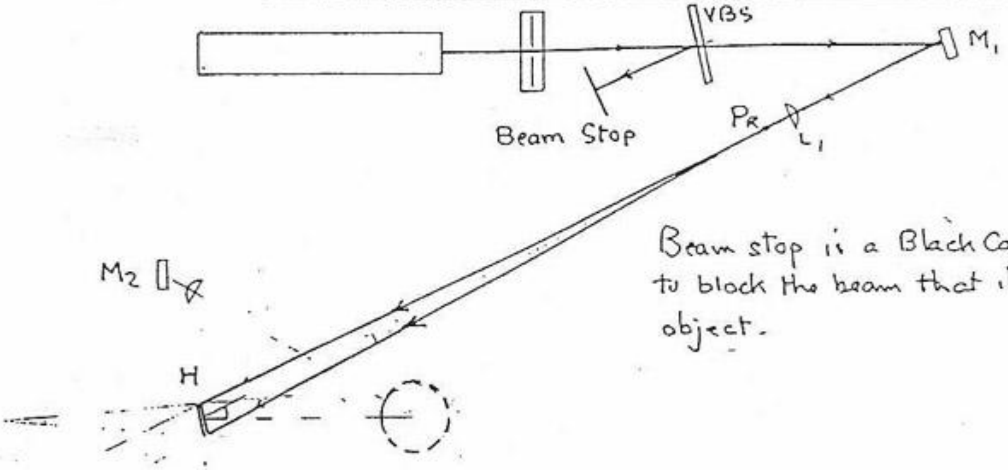


SH is a camera shutter

VBS is a variable beam-splitter

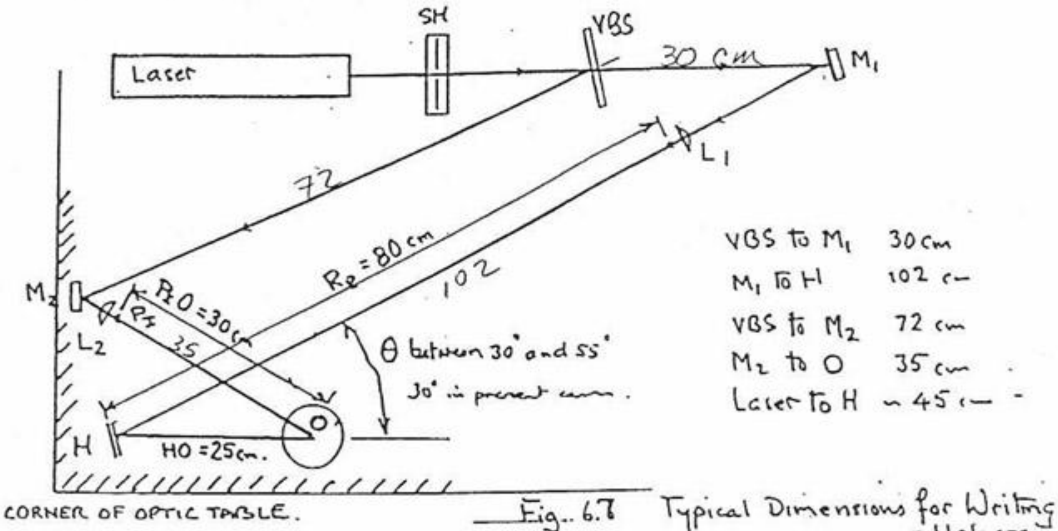
H is the holographic fil mounted in a 35 mm camera body, with lens removed.

Figure 6.5 Practical Apparatus for Writing Hologram



Beam stop is a Black Card inserted to block the beam that illumat the object.

Dimensions



VBS to M₁	30 cm
M₁ to H	102 cm
VBS to M₂	72 cm
M₂ to O	35 cm
Laser to H	~ 45 cm

Fig. 6.7 Typical Dimensions for Writing a Hologram

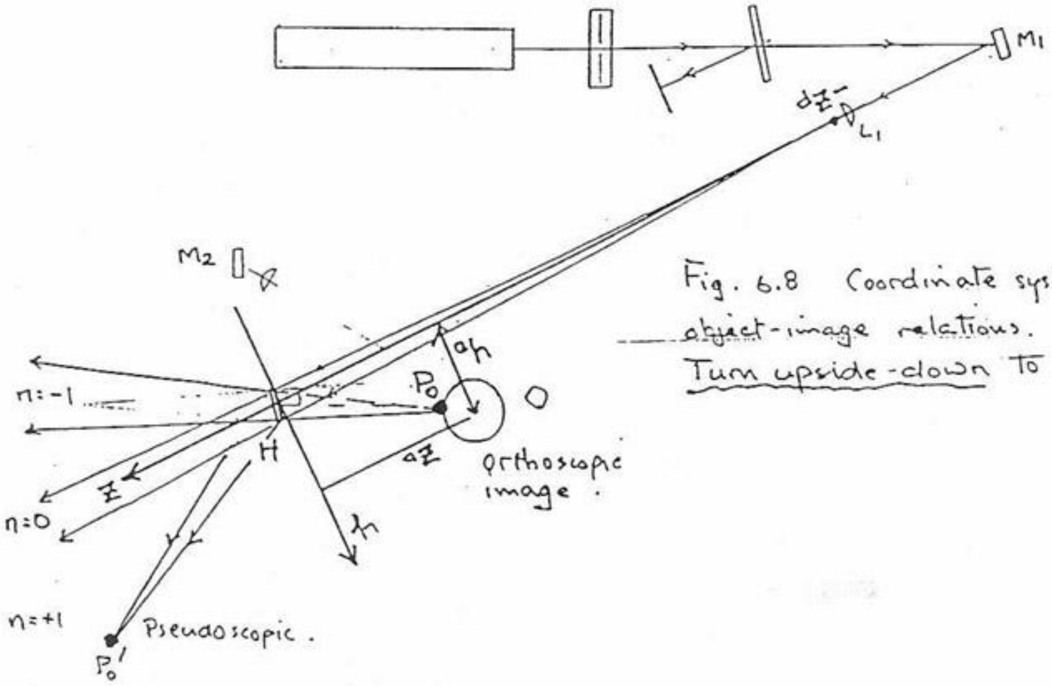


Fig. 6.8 Coordinate system for object-image relations.
Turn upside-down to read.

Processing of 35mm Kodak SO-253 Holographic Film

STEP	TIME	OPERATION
0. Transfer		Film from cassette to developing tank in total darkness. Keep film in darkness with lid on tank until film has been fixed.
1. Develop	5 min	-in Kodak D-19 developer at 20C(68F) with agitation
2. Rinse	30 sec	-in Kodak Stop solution at 18-21C (65-70F)
3. Wash	1 min	-in running tap water
4. Fix	5 min	-in Kodak Rapid-Fix solution with occasional agitation
5. Rinse	4 min	-in Kodak Hypo solution. **Hologram keeps longer with step 5, but can be deleted**
6. Wash	3 min	-in running tap water
7. Clear	3 min	-in Methanol solution
8. Wash	2 min	-in running tap water
9. Rinse	30 sec	-in Kodak Photo-Flo solution
10. Dry	slowly	at room temperature for your final hologram

Allow about 45 minutes to complete the processing.

Examine the hologram by eye. The degrees of blackening should be quite weak, with about 50% of the incident light being transmitted if you are to obtain a good bright holographic image.