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Quality aspects of holographic image deblurring

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QUALITY ASPECTS
OF HOLOGRAPHIC IMAGE DEBLURRING

BY

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and
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requirements for the degree of Bachelor of Science in the
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Thesis Advisors: Dr. Norman R. Goldblatt, Professor John F. Carson
and Dr. E. M. Granger

ABSTRACT

The process of holographic image enhancement was investigated with respect to image quality. A maximum improvement in MTF of 60% was achieved. The process itself was found difficult due to the critical natures of many of its steps. The theory of image enhancement by optical processing is explained in detail and the reasons for using a holographic filter are discussed.

CONTENTS

APPENDIXES

ILLUSTRATIONS

Illustrations (Cont'd)

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CHAPTER I

STATEMENT OF OBJECTIVES

1.1 DEFINITION OF THE PROBLEM

Image enhancement by means of coherent optical processing is a powerful and proven technique. With optical processing, halftone dots and rastor lines can be removed from images, contrast can be enhanced, and image sharpness can be improved.

One of the methods for increasing the sharpness of a photograph involves the use of a fourier transform hologram made from the unwanted spread present in the system as a spatial filter in the coherent processor. This filter, known as a Van der Lugt filter, can only be produced when the spread function of the photograph is known and can be simulated.

Although the literature shows much effort in the field of holographic image enhancement, most of the work has been conducted by electrical engineers with little respect to the methods of image evaluation which could be employed to describe the quality aspects of the blurred image as well as the corrected image.

1.2 PURPOSE OF THE INVESTIGATION

Vague references to the quality of the enhanced image such as, "In many cases the deblurring may result in a practically almost perfectly sharp and completely faithful image,"[1] leave great question to the effectiveness of such enhancement techniques.

The literature states little about the effects of noise in the hologram and its effect on the enhanced image. Although some published results demonstrate great visual improvement of a scene, the defocus is not well defined and quality results become questionable* in a less than perfect system.

It is our intent to investigate some of the limits of this process in terms of objective image quality criteria while keeping in mind the relationships between objective and subjective criteria.

The quality of the defocused image will be compared to the quality of the best obtainable correction. Difficulties encountered and methods for optimizing the process will also be discussed.

1.3 METHOD OF INVESTIGATION

The major steps in the investigation are outlined below:

1. A thorough investigation of the literature was conducted to determine the steps of the process and the type of results that could be expected.

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*All references are contained in the bibliography at the end of this document.

2. Sensitometric tests were conducted on the photosensitive plates to be used for recording the hologram and also the film to be used for the blurred and corrected images. The exposures and development times for achieving specified gammas and densities were determined. A photocell was calibrated to measure the illuminance incident from the laser thus enabling the exposure time to be calculated.

3. An interferometer was constructed to test the stability of the floating holographic table used for making the Van der Lugt filters as well as the coherent optical processor. To further test the stability of the table as well as the optical components of the system, transmission holograms were made of test objects and reconstructed to allow a visual check of the quality of the hologram the system was able to record.

4. A standard resolution target, a pinhole, and a standard test scene were blurred in a known and identical manner on a specially constructed blurring apparatus. This blurring was repeated using different blurring functions to simulate different types of errors which may blur a photograph.

5. A Van der Lugt filter was made from each of the blurred pinholes. Different beam ratios and exposures were tried to determine the best holographic filter.

6. Using the Van der Lugt filter as a spatial filter in the coherent optical processor, the test target was deblurred.

7. The original test target, the blurred test target, and the corrected target were all scanned on a microdensitometer and the modulation transfer function of each of these targets was plotted as a function of frequency.

8. The MTF's of the targets were compared to identify any changes in the image quality. The images were also judged visually and compared.

CHAPTER II

TYPES OF BLUR

2.1 INTRODUCTION

For the purposes of image enhancement, it is necessary to know the exact blur that is to be removed from the image. If the type and cause of blur is known, the spread function could be recreated in the laboratory.

2.2 MISFOCUS

A perfect image would be one which resembles the original in every way. The world is three dimensional and it is impossible to accurately record all three dimensions on a two dimensional plane such as film. Even if the original is a two dimensional object such as a test target, the lens must be focused on the proper plane or a misfocus will occur in the image.

Figure 2.1 shows the type of error that can be introduced by focusing a system behind or in front of the subject of interest. It should be noted that in a real system degradation will occur at the edges of the blur circle.

In the context of image enhancement, this type of error would also apply to an object which may be in the background of a photograph which has been intentionally focused on some other subject. If circumstances necessi-

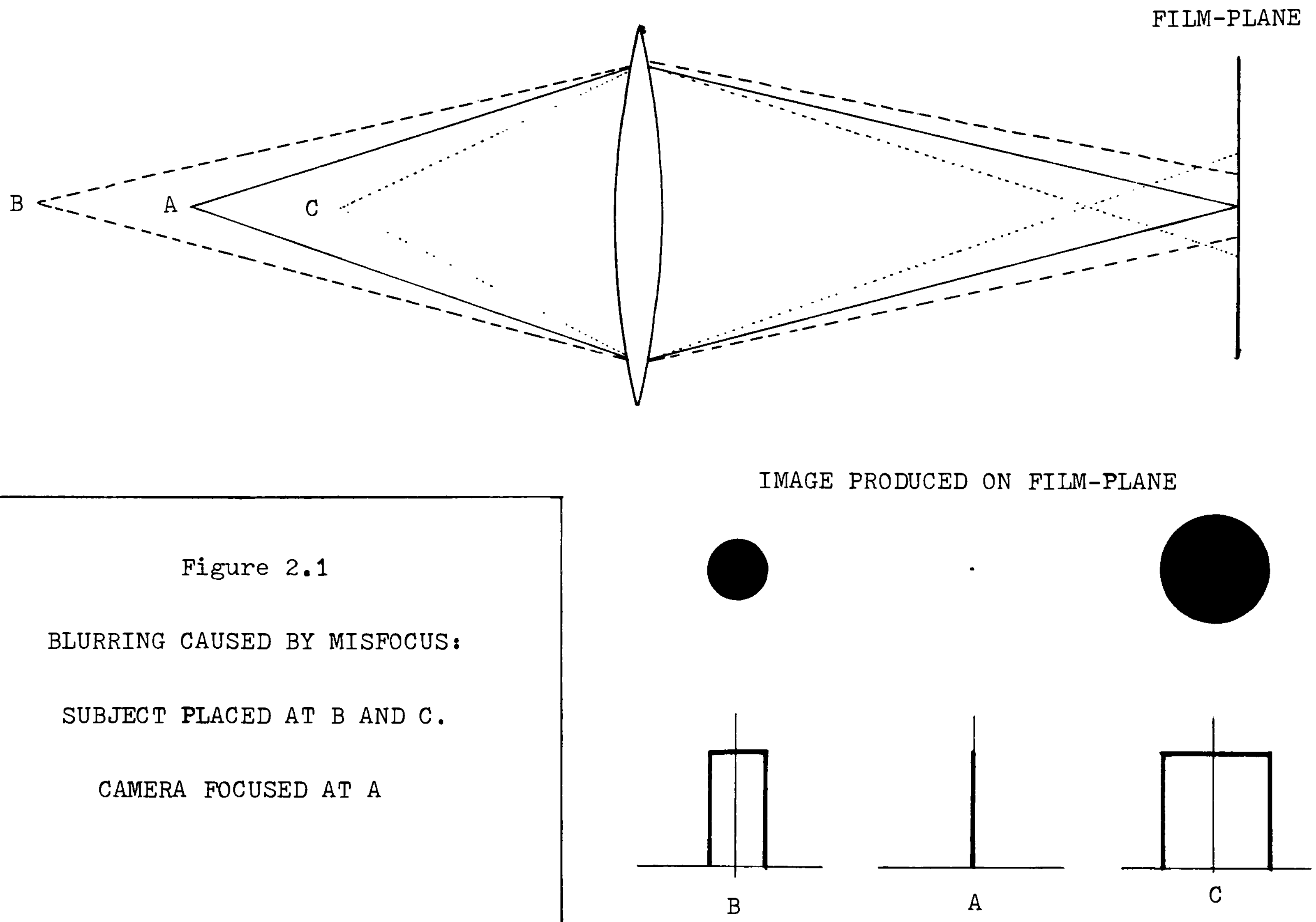


Figure 2.1

BLURRING CAUSED BY MISFOCUS:

SUBJECT PLACED AT B AND C.

CAMERA FOCUSED AT A

tated the extraction of information about some background object, it would be treated as a misfocus problem.

2.3 IMPROPER POSITIONING OF THE FILM PLANE

If the film plane in an optical system were shifted or improperly placed, a blur circle similar to that caused by misfocus would occur. This is shown in figure 2.2.

2.4 LINEAR MOTION

One of the most common causes for blur in a photographic system is motion. The simplest case of motion would be blur due to linear motion in which case either the optical system or the object would be moved during the time of exposure.

Figure 2.3 shows the type of blur which could be expected in the cases where the blurring is caused by linear motion.

2.5 OTHER BLUR

Other causes for blur in photographic systems include the object and image planes being out of parallel and other types of motion combinations of any or all of the aforementioned.

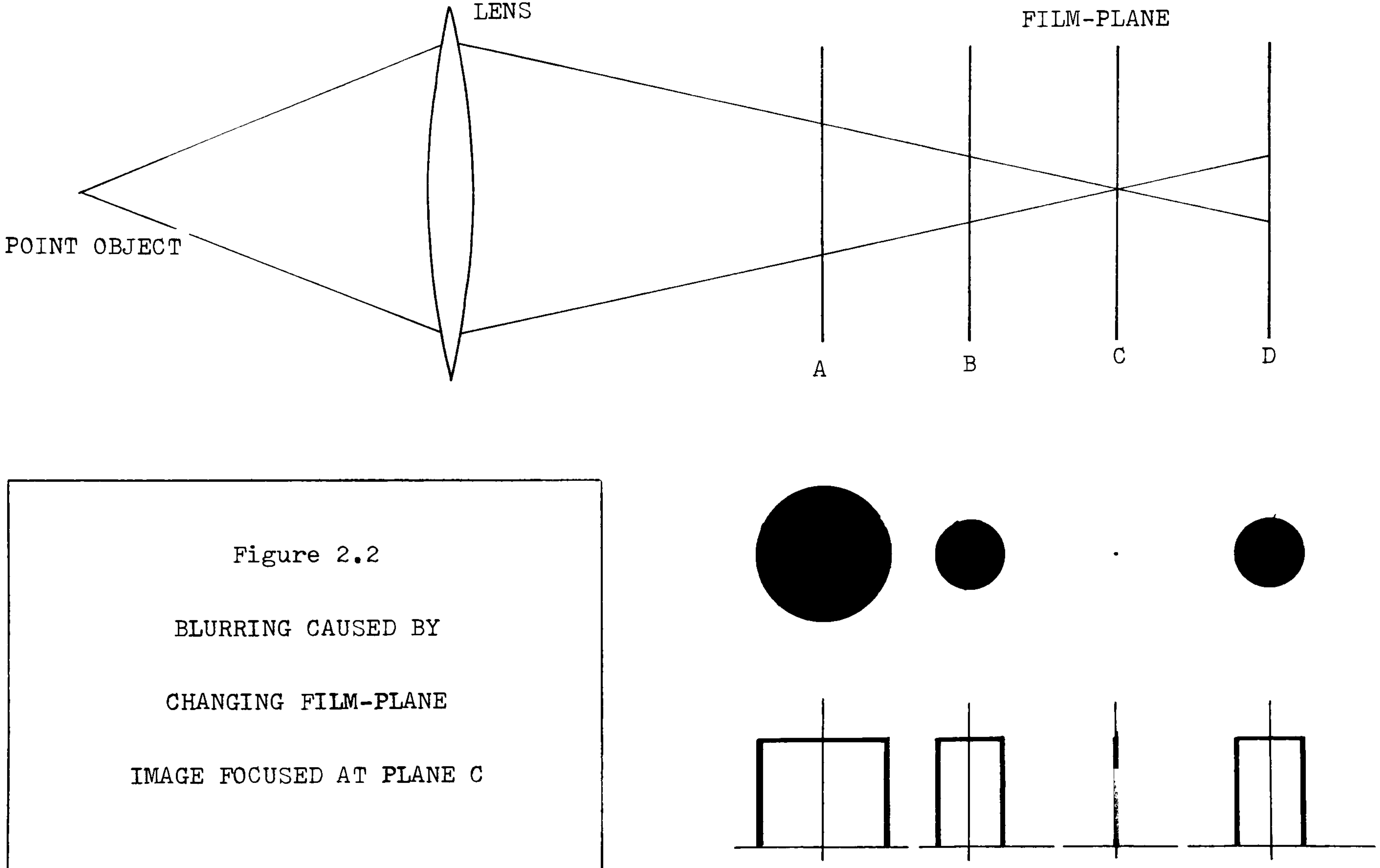
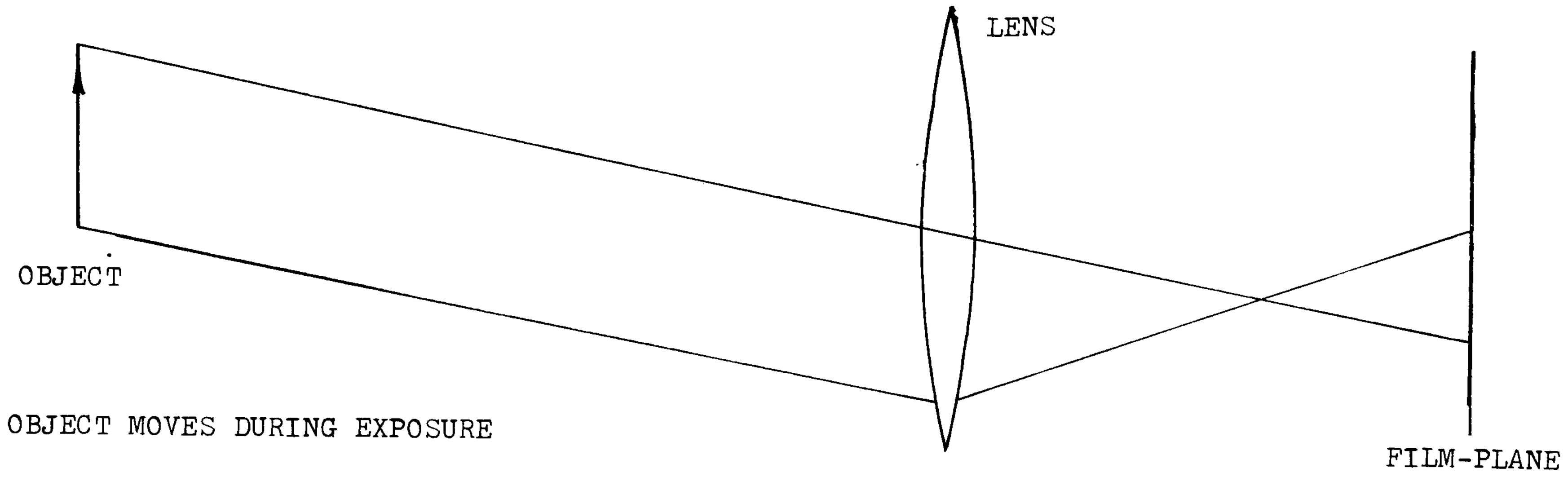


Figure 2.2

BLURRING CAUSED BY

CHANGING FILM-PLANE

IMAGE FOCUSED AT PLANE C



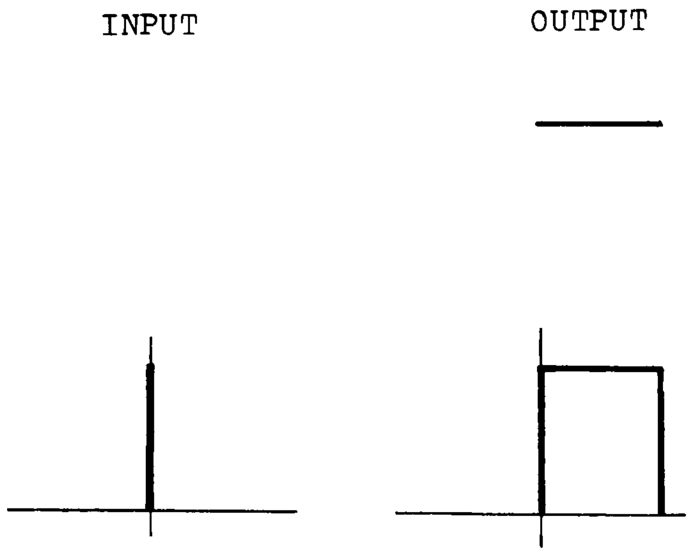


Figure 2.3

BLURRING CAUSED BY SUBJECT

MOTION DURING TIME

OF EXPOSURE

CHAPTER III

SPATIAL FILTERING AND COHERENT OPTICAL PROCESSING

3.1 INTRODUCTION TO OPTICAL PROCESSING

One of the most basic theorems of mathematics is that the whole is equal to the sum of its parts. If something were broken down into its component parts, a changed version of the original would be the result. If the parts which were deleted were done by selection, the original would be filtered; the result being the original changed in a specific manner.[2]

If an object were optically separated into some recognizable components, and some of these components selectively removed, the image of the object could be changed in a pre-determined manner.

A lens can be forced to operate with an infinite focal length by placing the object at the focal point of the lens and taking the image at the back focal point since

$$\frac{1}{s'} - \frac{1}{f} = \frac{1}{s}$$

where f is the focal length, s is object distance and s' is image distance.[3] Since under the described conditions $s' = s = f$, the equation will only work when f is infinite.

Using the wave theory of light, it has been shown that when the lens is operating with an infinite focal length, a Fraunhofer diffraction pattern would be realized at the back focal plane of the lens.[4] The input illumination consists of waves of varying amplitudes and the Fraunhofer pattern is a function of the frequencies of the input object.

Fourier has shown that if a function is periodic, it can be broken down into a series of sine and cosine functions.[5] It has been mathematically proven that the Fraunhofer diffraction pattern is the Fourier transform of the object.[6] Since the image is related to the input frequencies of the object which are spatial in nature, the Fourier transform of the object is said to be the spatial frequency spectrum of the object.[7]

This frequency spectrum then, represents the original input as a function of frequencies. If some of these frequencies are selectively removed and the original is reconstructed, the original would be spatially filtered or more generally, optically processed.

3.2 THE BASIC OPTICAL PROCESSING SYSTEM

The basic optical processing system is shown in figure 3.1. A laser source provides coherent monochromatic light which is spread by a microscope objective.

The light is then collimated by the first lens be-

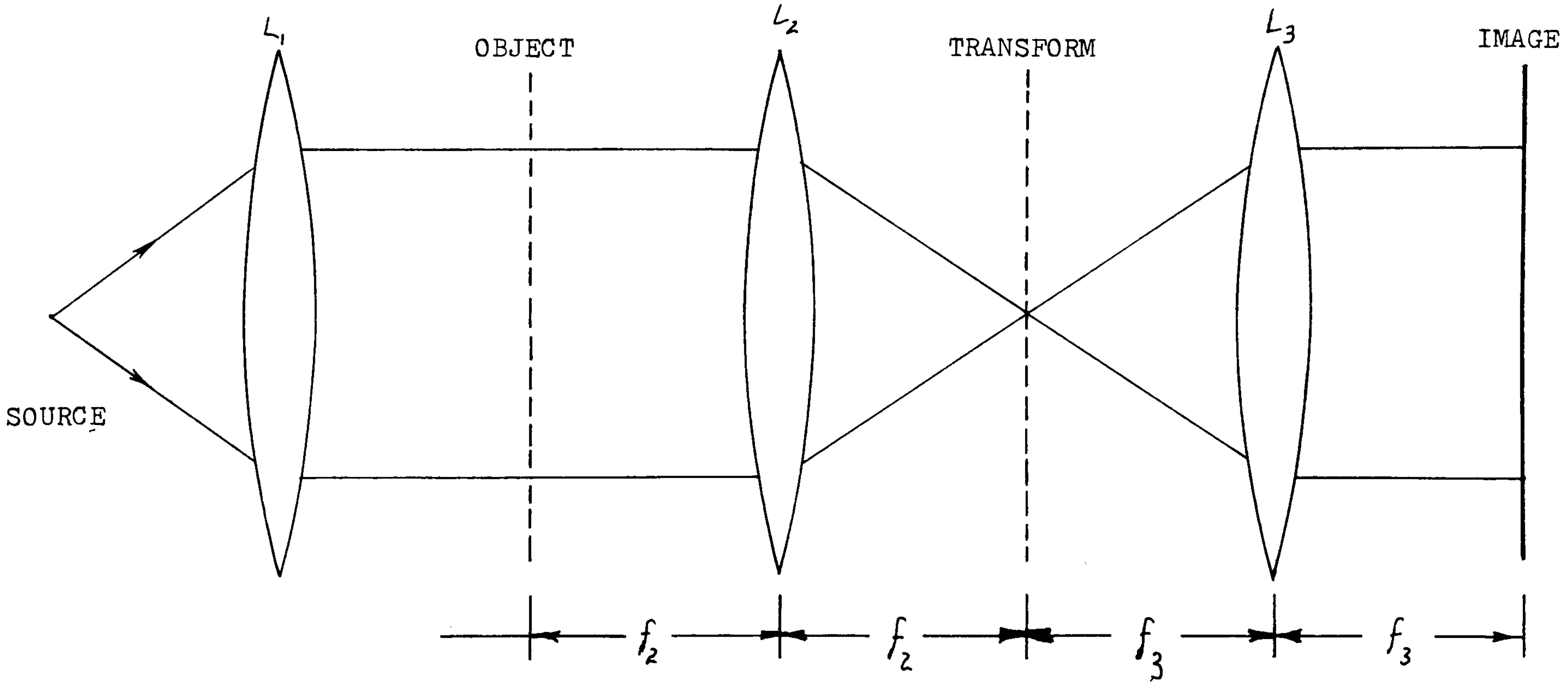


Figure 3.1 - THE OPTICAL PROCESSOR

fore passing through a transparent object which is located at exactly one focal length in front of the second lens. As was discussed earlier, the precise Fourier transform of the object would be found in the back focal plane of lens 2.

This is the two dimensional output of the spatial frequency spectrum of the object. If the object were a constant such as a neutral density filter, a single point would appear in the back focal plane of the lens because a point is the Fourier transform of a constant. (For the sake of simplicity, the system is assumed perfect.)

Placing another lens (lens 3) one focal length from the transform plane retransforms the components to a facsimille of the original object, one focal length behind the lens.

If part of the information in the Fourier transform plane is removed, altered or filtered, the reconstruction will differ in some manner from the original and will have been optically processed.

3.3 THE FOURIER TRANSFORM

It is important to understand exactly what image is formed in the Fourier plane. The low frequency information will be found on or about the optical axis. The higher frequency information will be found furthest from the optical center. Co~~u~~arse information in the original produces low frequency information. Fine detail in the original such as sharp edges produces the high frequency information.

Information which is vertical in the original will produce spatial frequencies along the horizontal axis. Information in the original which is horizontal will also be rotated 90 degrees to a vertical plane in the transform.

A circular aperture is represented graphically in figure 3.2 where A is the diameter and B is the intensty of the incident illumination.

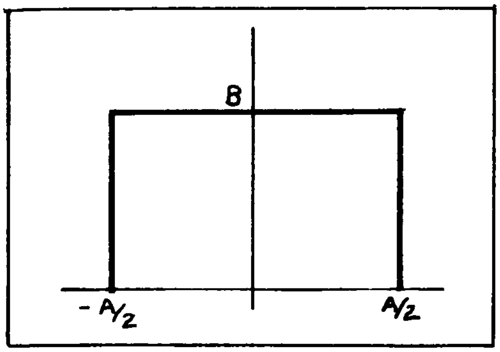


Fig. 3.2

The Fourier transform of such a function is shown in figure 3.3. The function is a sinc function with a period equal to 2A.

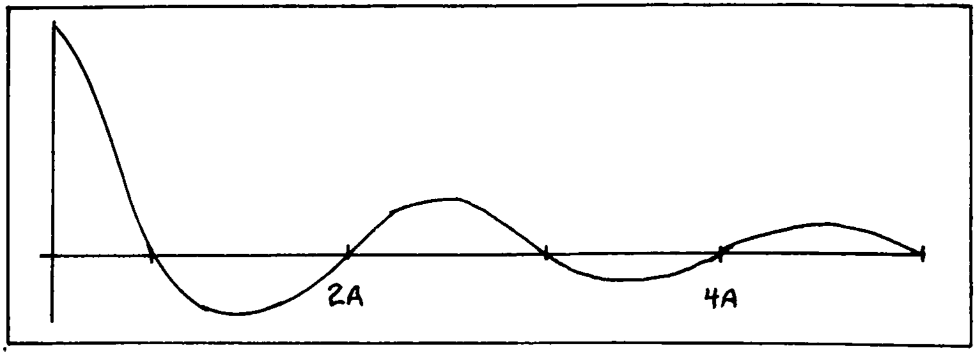


Fig. 3.3

3.4 IMAGE ENHANCEMENT BY OPTICAL PROCESSING

A simple theoretical case of image enhancement can now be examined. Figure 3.4 shows an optical processor as a black box system. A circular aperture is used for an input object as the representation of the blur circle of a perfect point. The optical processor must somehow change the blur circle back to a point.

The Fourier transform of the aperture has been described as a sinc function. In the case where the aperture is circular and thus symmetrical, the resulting three dimensional transform consists of apparently alternating light and dark bands. This type of transform is known as an Airy disc after Sir George Biddle Airy.[8] The Airy disc is then present in the Fourier plane as shown in figure 3.5.

The question arises as to what transform is needed at the Fourier plane to be retransformed to form the point, which is the desired output of the system. As was discussed earlier, the transform of a point (delta function) is a constant (even illumination). Figure 3.6 shows the desired output and required transform. If a method could be found which could change an Airy disc to an even illumination in the transform plane, the aperture could be reduced to a point.

If a positive transparency were sandwiched with a

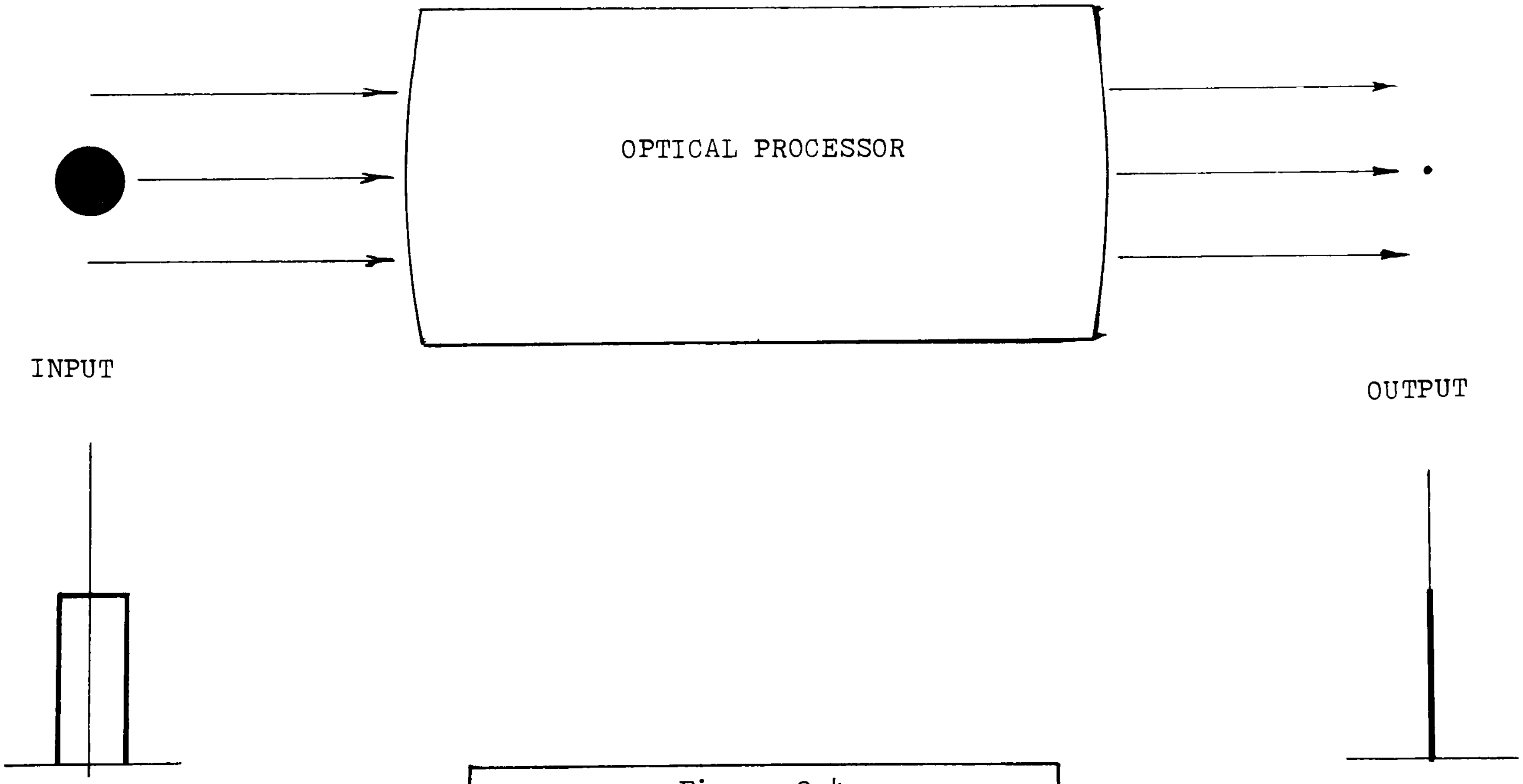


Figure 3.4
OPTICAL PROCESSING
FOR IMAGE ENHANCEMENT

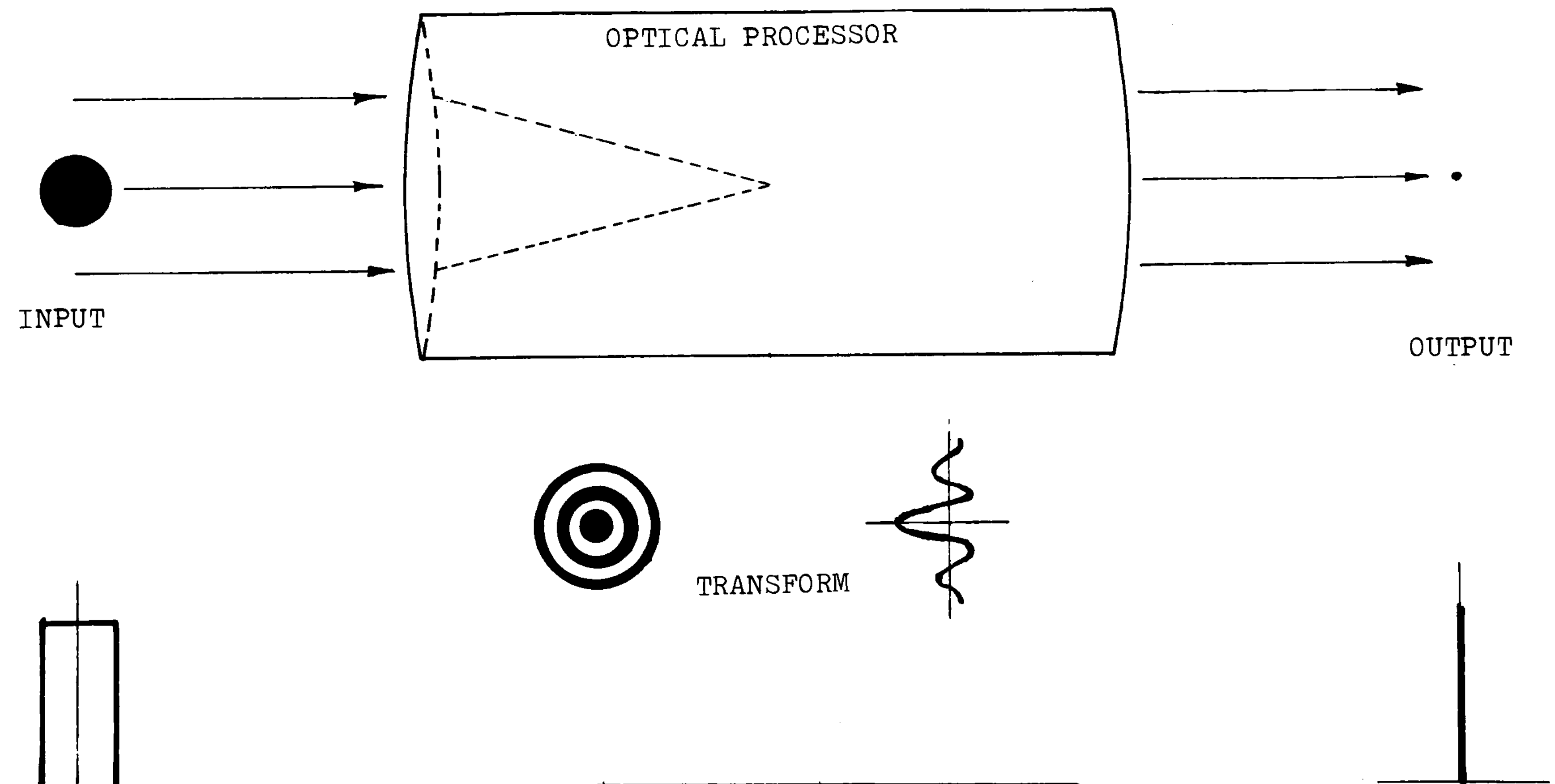


Figure 3.5
TRANSFORM OF INPUT
PRESENT IN FOURIER PLANE

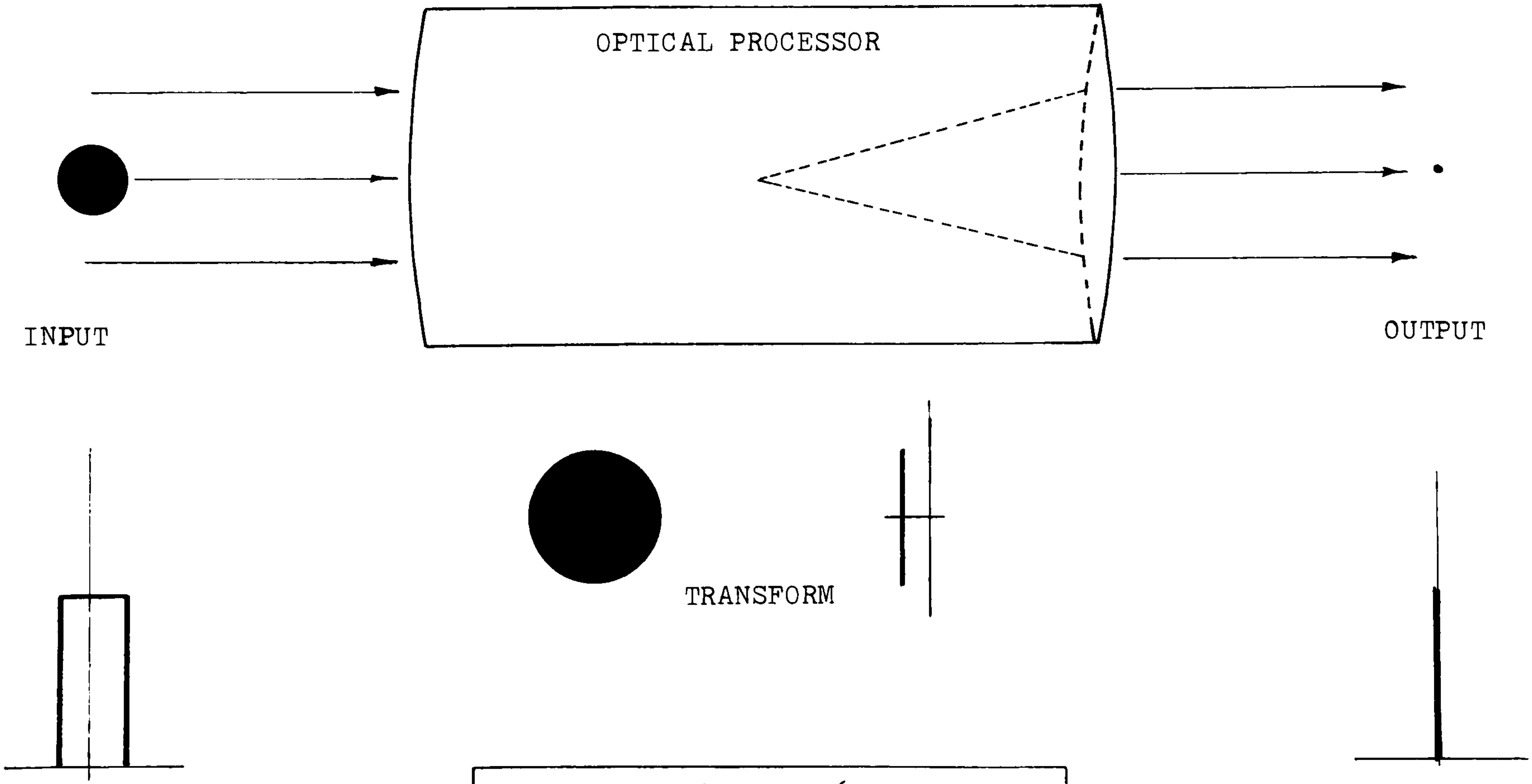


Figure 3.6
TRANSFORM REQUIRED
FOR DESIRED OUTPUT

negative transparency of the same image at the same contrast, the result would be a neutral or constant illumination. The actual transform may be considered as the positive. If this were recorded on film and the film processed, a negative of the transform would result. Figure 3.7 shows this result.

Then, if the negative were properly positioned in the Fourier plane of the optical processor, the aperture could be corrected to form the point.

3.5 AMPLITUDE CORRECTION

A point, although usually desirable as the output of an optical processor, when used for deblurring, ia unachievable. It would be safe to suggest that the closer the blurred image of a point (more realistically the blurred image of a pinhole) could be transformed to the dimensions of the original point (multiplied by any magnification factors that the system might introduce), the more corrected that the output image would have to be.

Again, it is necessary to examine the transform of a typical blur circle. The transform or Airy disc is shown graphically in figure 3.8.

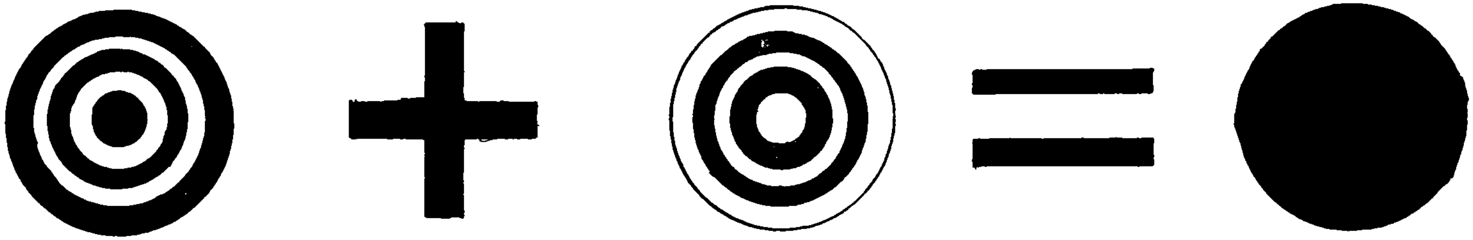


Figure 3.7

OVERLAYING POSITIVE ON NEGATIVE

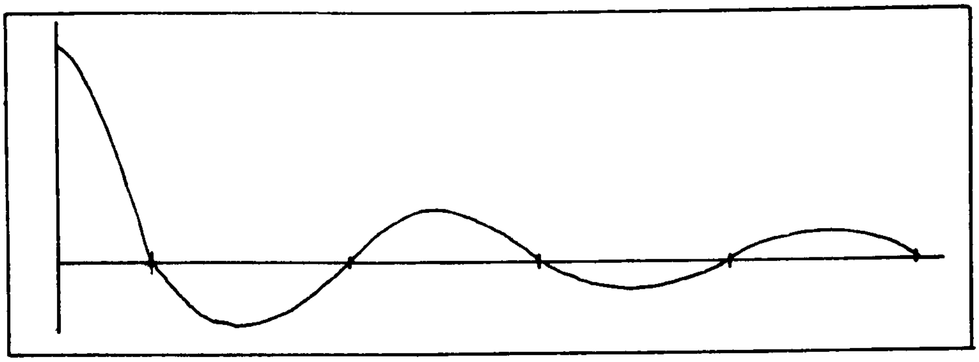


Figure 3.8 - Transform of Blur Circle

Ignoring the negative portions of the transform which will be discussed later, a curve drawn through the peaks would result in a function which would decrease sharply and then become asymptotic as shown in figure 3.9.

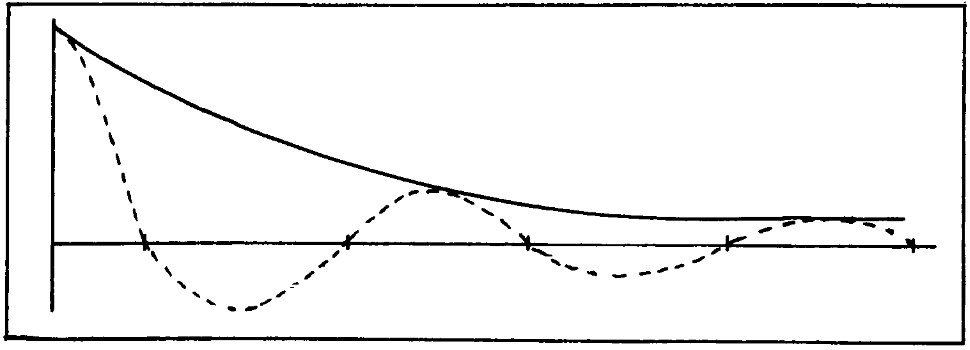


Figure 3.9 - Asymptotic Function

The function begins to appear constant after moving some distance from the vertical axis. If the intensity of the central portion of the Airy disc (the zero order) were reduced, the function would more closly resemble that which is desired. If a small black dot were used as a filter on the zero order of the transform, the new transform would appear as in figure 3.10. The dotted line demonstrates the shape of the function.

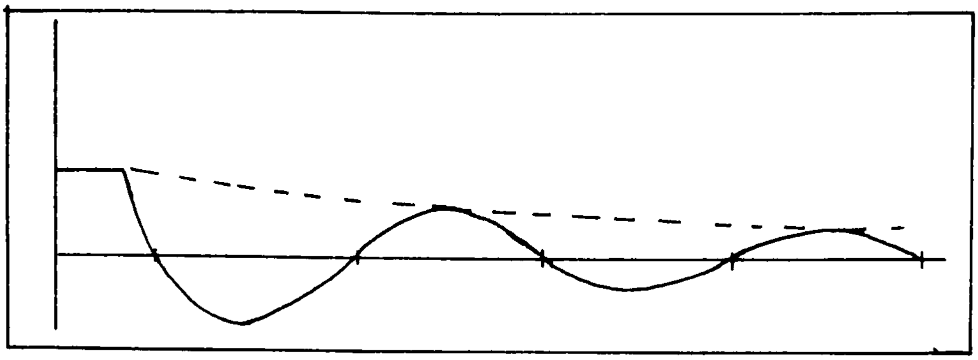


Figure 3.10 - Corrected Transform

Since the enhancement is obtained by chopping off the amplitude of the transform, this process is known as amplitude correction.

It can be easily seen that if a series of concentric circles or more properly, the negative Airy disc, were placed in the system as a filter, more correction would result.

3.6 SPATIAL FILTERING FOR PHASE CORRECTION

As discussed in the previous section, the transform has negative values. These negative values correspond to phase shifts or spurious resolution in the blurred image. The points where the transform cross the axis represent frequencies which have a contrast of zero. A phase filter would serve the purpose of inverting the negative portions of the transform to produce a transform of the type displayed in figure 3.11.

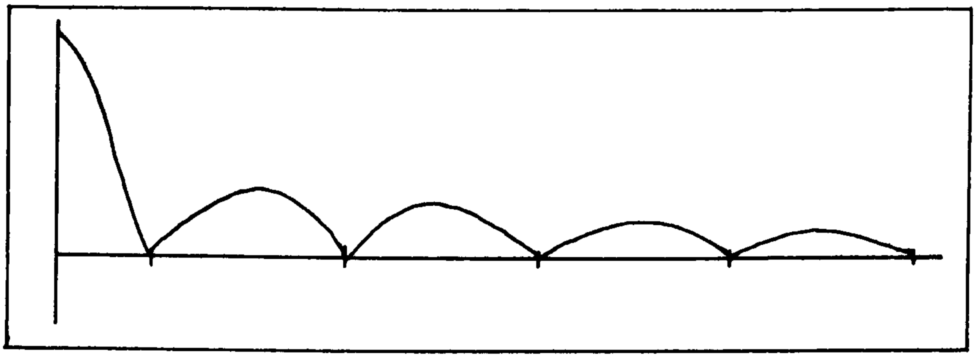


Figure 3.11 - Corrected Transform

3.7 CONVOLUTION

The need for the phase filter can best be shown by looking at the optical processor in terms of the mathematical convolutions it performs.

If we designate some original scene as f(x,y) and introduce some blur into system represented by h(x'-x,y'-y), the blurred scene would be represented as

$$g(x',y') = \iint_{-\infty}^{\infty} f(x,y)h(x'-x,y'-y)\,dx\,dy \qquad (3.1)$$

The object of deblurring is to deconvolute the function represented in equation 3.1 to return to the original function f(x,y). One of the basic theorems of Fourier analysis is that the convolution of two functions is equal to the product of their Fourier transforms.[9]

Taking the Fourier transforms of both sides of equation 3.1 yields the expression

$$G(u,v) = F(u,v)H(u,v) \qquad (3.2)$$

where the capital letters designate Fourier transforms. By dividing both sides of the equation by H(u,v), the equation can be solved for the Fourier transform F(u,v)

$$\frac{G(u,v)}{H(u,v)} = F(u,v) \qquad (3.3)$$

where F(u,v) is the transform of the original unabberated object.

Thus the filter needed to deblur the transform G(u,v) must be the transform 1/H(u,v) or the equivalent. If the transform of the spread were recorded, the filter would represent the transform $1/|H|$ since. only the intensity would be recorded. This would then be the amplitude filter. It can be shown mathematically that

$$\frac{1}{H} = \frac{e^{-i\phi}}{|H|} \qquad (3.4)^{10}$$

where $e^{-i\phi}$ represents the phase of the transform. Thus both the amplitude and phase correction is needed to obtain the best correction of the blurred target.

The convolution also points out one of the pitfalls of image enhancement. Convolution widens the function or in the case of images, would spread them out even further. However, the peaks of the functions become intensified making the central portions more intense. Figure 3.12 shows the convolution of a blur circle with itself.

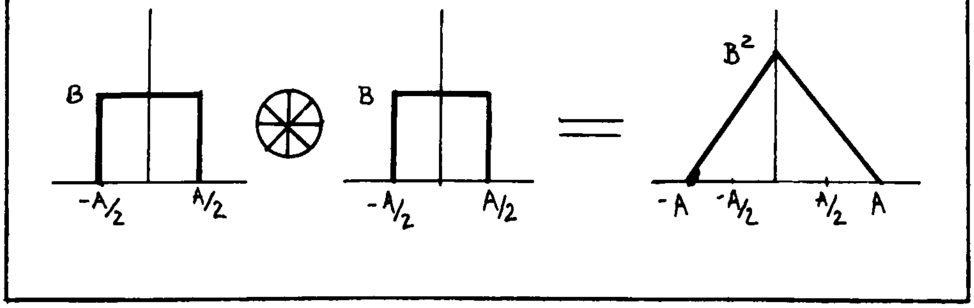


Figure 3.12 - Convolution of a Blur Circle

Theoretically, this should be corrected to a single point, however, convolution shows that this is not the case as the function is actually widened. The convolution approximates the delta function more closely than the blur circle does and represents improvement in the image.

CHAPTER IV

THE VAN DER LUGT FILTER

4.1 INTRODUCTION

Classically, the amplitude filter was made using photographic film or the evaporation of a substance onto a substrate. Phase filters were frequently fabricated by evaporating transparent film of appropriate optical thickness, bleaching film, or the use of dichromated gelatin films. However, it has been shown by A. B. Van der Lugt that holography can produce the two filters simultaneously on a single piece of photographic film for any transfer function and consist of patterns of absorption only. Thus the two filters may be replaced by a single filter making both corrections.

4.2 INTRODUCTION TO HOLOGRAPHY

Holography is the recording on a photographic material of the interference pattern between two coherent and usually monochromatic light beams. One beam is brought directly to the photographic material as a reference beam while the second beam is altered by reflection off or transmission through some object to be recorded.

In holography, the visibility of the fringe (interference) pattern is a function of the optical path difference between the object and reference beams. The visibility is at a maximum when the difference is zero, or an even multiple of the coherence length of the light.

The fringe pattern is also affected by the relative intensity of the two beams at the plane where the hologram is recorded. The reference beam must be at least twice as intence as the object beam to get sufficient contrast. The reference beam may even be 100 times as bright in some cases.

When the hologram is processed and replaced in the reference beam, the beam is diffracted as it passes through the hologram to form a reconstruction of the object.

4.3 THE VAN DER LUGT FILTER

The Van der Lugt filter is realized by the combination of the abberated wavefront in the Fourier transform plane with a plane wave brought to the transform plane as a reference beam. The angle between the reference beam and the optical axis of the optical processor (θ) is important for determining the type of film necessary for recording the filter. The angle is shown in fig. 4.1.

For a general case, this holographic filter can be shown mathematically to contain both the amplitude and

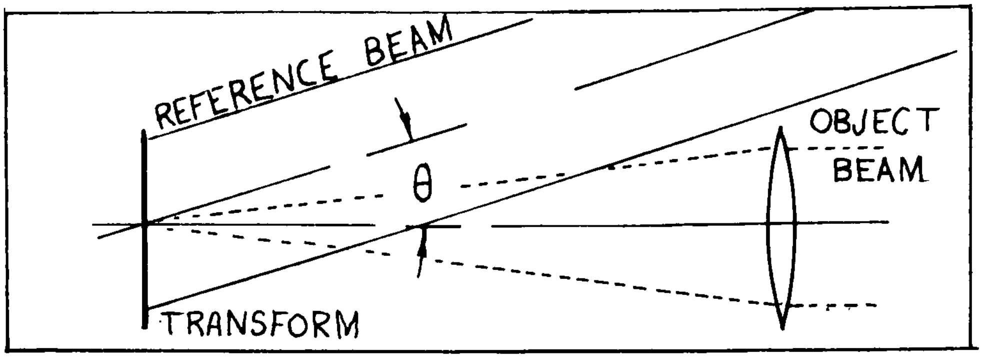


Figure 4.1 - Beam Angle

phase information needed for deblurring. The aberrated wavefront, i.e. the Fourier transform of the spread function of a point, can be represented mathematically

$$O = O \exp(j\, \Phi(x,y)) \exp(j\, (k_y - K_z Z))$$

where $\Phi(x,y)$ represents some arbitrary phase object and the reference beam $A = A \exp(j(K_y Y + K_z Z))$. The reference beam comes in at some angle $\theta = \tan^{-1}(K_y/K_z)$.

The film for recording the Van der Lugt filter must be processed to a gamma of 2 as shown in section 4.4. Since the gamma is 2, the mathematical square of the interference is recorded. The squaring results in the intensity function which can be represented as a function of x and y.

$$I(x,y) = A^2 + O^2 + 2AO \operatorname{Cos}(2K_y Y - \Phi(x,y)$$[11]

In the specific case of a sinc function, the interference pattern will result in the following:

$$I = (\operatorname{sinc} x + e^{iwx})(\operatorname{sinc} x + e^{-iwx})$$

By multiplying the expression it is found that the intensity (I) can be represented as

$$I = \text{sinc}^2 x + (\text{sinc } x)(\text{Cos } wx) + 1$$

where w is the spatial frequency.

The amplitude information will be stored in the $\text{sinc}^2 x$ term and the phase information will be stored in the (sinc x)(Cos wx) term. The constant will only raise the overall exposure. It can be seen that the proper information results onto a single photographic plate by coding the information on the hologram.

A Van der Lugt Filter is shown in figure 4.2.

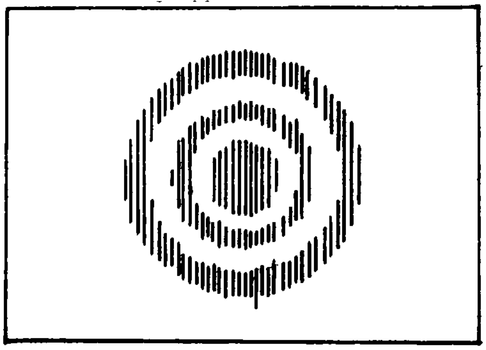


Figure 4.2 - Van der Lugt Filter

4.4 SENSITOMETRY

In order to see why a film having a gamma of two is necessary, some mathematics of the process will be evolved. Let α be the transmission factor of the photographic plate. Then, the transmission factor for the intensity is

$$t(I) = \alpha\alpha^* \qquad (4.1)$$

where α^* is the complex conjugate of the transmission factor.

Density is equal to the negative of the log of the transmittance, hence

$$D(I) = -\log_{10}\alpha\alpha^* \qquad (4.2)$$

From the characteristic curve of a photographic material, the density can be described as a function of exposure by the expression

$$D = D_o + \Gamma \log_{10}\left(\frac{E}{E_o}\right) \qquad (4.3)$$

where Γ is the slope of the straight line portion of the characteristic curve, D_o and E_o are constants pertaining to the base density of the film, and E is the exposure level of the film.

Substituting the transmittance for the density in equation 4.3, the relationship becomes

$$-\log_{10}t = -\log_{10}t_o + \Gamma\log_{10}\left(\frac{E}{E_o}\right) \quad (4.4)$$

Algebraically simplifying equation 4.4, it can be written as

$$t = t_o\left(\frac{E}{E_o}\right)^{-\Gamma} \qquad (4.5)$$

For pure absorbtion without a phase change, α is a real number equal to the square root of the intensity transmittance. Thus,

$$\alpha = \sqrt{t_o \left(\frac{E}{E_o}\right)^{-\Gamma}} \qquad (4.6)$$

Simplifying equation 4.6, α is shown to be related to the exposure raised to the negative ½ gamma, as shown in equation 4.7.

$$\alpha = t_1 \left(\frac{E}{E_o}\right)^{-\Gamma/2} \qquad (4.7)$$

To make the photographic plate proportional to the original intensity distribution, a gamma of -2 would make t related to the ratio of exposures

$$t = t_1 \left(\frac{E}{E_o}\right)^{-(-2/2)} = t_1 \left(\frac{E}{E_o}\right) \qquad (4.8)$$

The fact that the gamma is negative refers to the plate being the negative of the intensity distribution. This is the case which is recorded by the Van der Lugt filter.

4.5 RECONSTRUCTION

When the processed Van der Lugt filter is replaced in the Fourier plane and the reference beam removed for reconstruction, the object beam is then diffracted and three distinct beams are seen leaving the hologram.

The blurred target made with the same blur as the object the filter is made from replaces the filter in the input plane and the three beams each have a specific identity.

If the undiverted beam is examined, the zero order, or amplitude correction will be found.

The beam that appears where the reference beam was will contain the convolution of the blurred target with its spread function or the deblurred image.

The beam which is complimentary to the reference beam contains the cross correlation of the blur with its spread function. In the cases where the spread functions are symetrical, this is identical to the convolution.

Figure 4.3 shows the location of the reconstructions.

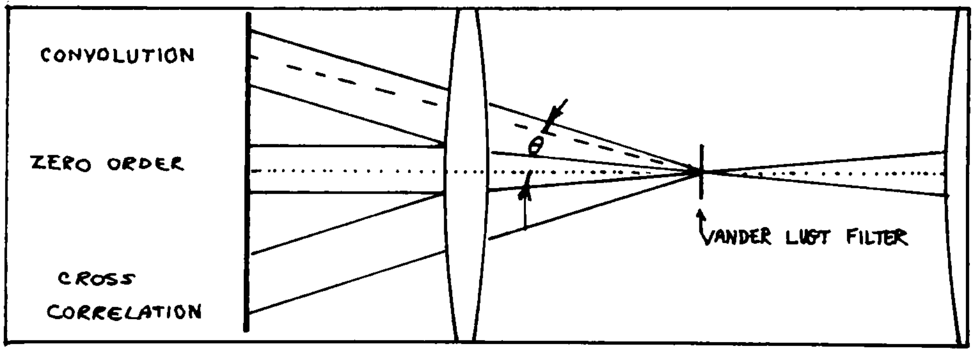


Figure 4.3 - The Reconstruction

4.6 EFFICIENCY OF THE VAN DER LUGT FILTER

In the case of optical processing, the Van der Lugt filter is a hologram used as a filter. Since filtering is taking place, the reconstructed image will obviously be less intense than it would be had a reconstruction been made without filtering.

The amplitude filtering is essentially placing density in the path of the illumination and thus the efficiency should be rather low. In reality, the theoretical limit for the efficiency of a thin hologram used as an amplitude filter is only 6.25%.[12] This means that only 6.25% of the illumination which reaches the filter will pass through it.

At the same time, the hologram is dividing the beam into three beams and lowering again the level of light. Theoretically, a maximum of 33.9% of the illumination will be found in either of the two side beams which is where deblurring occurs.

When considering the total efficiency of the filter, the efficiency of each component is multiplied to determine the overall efficiency. In the case of a Van der Lugt filter, therefore, the theoretical maximum efficiency is only 21.2%.

These efficiencies are the maximum as theoretically predicted. Experimentally, the measured highest obtainable efficiencies were even lower.

CHAPTER V

LABORATORY SIMULATION OF BLUR

5.1 INTRODUCTION

For the purpose of experimentation it is more logical to create the blurred images in the laboratory rather than to intentionally misfocus a camera or move the camera or subject during the exposure.

For the purposes of image enhancement, the blur must be known. However, the filter ? produced to deblur one photograph may be used to correct others if they have been blurred in the exact same manner.

By creating the blur on an optical bench the identical blur can be introduced on the necessary targets, test scenes, or other images to make quality evaluations through the system. A pinhole placed in the system can be blurred in the identical manner producing a picture which closely resembles the spread function of a point imaged in the same system.

5.2 THE APPARATUS

The method used for introducing blur to the test scenes is shown in figure 5.1.

A light source is placed on an optical bench behind a ground glass. The lens is used as a collimator by placing it precisely one focal length from the ground

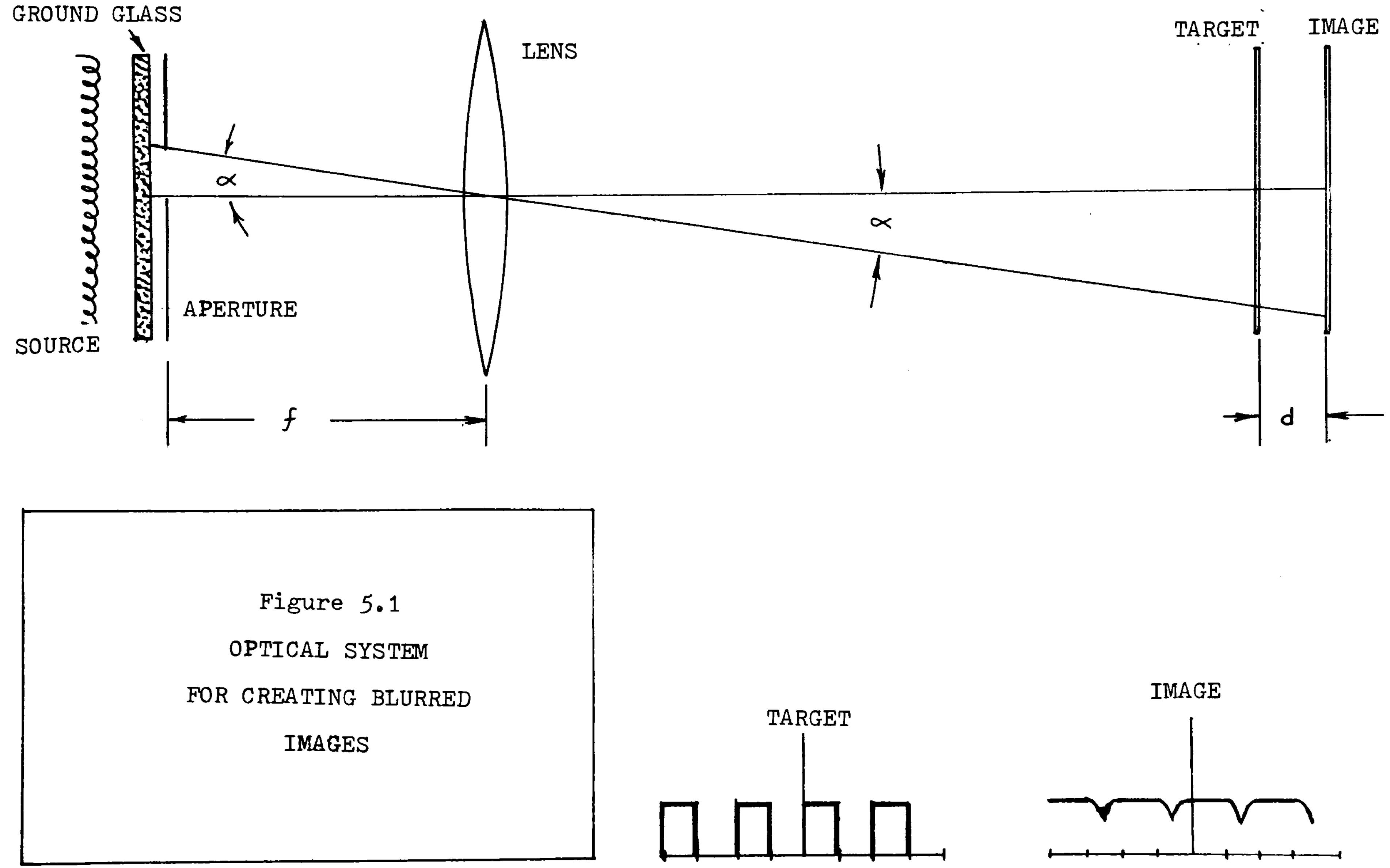


Figure 5.1
OPTICAL SYSTEM
FOR CREATING BLURRED
IMAGES

glass. Two film holders are placed at a fixed distance from each other. Apertures placed on the ground glass change the amount of defocus between a scene placed in the first film holder and a receiving piece of film placed in the second holder.

5.3 TYPES OF APERTURES

Each aperture placed on the ground glass introduces a different blur to the sytem. If a pinhole were placed on the ground glass, the sharpest image would occur, but the illumination passing through the system would be decreased substantially. The effect is similar to increasing the depth of field by using a small f-stop in a camera.

If a narrow slit which can be used to represent linear motion is placed above the optical axis with a height of A as shown in figure 5.1, the illumination forms a half angle with the optical axis. Each point in the test scene is then spread by the same half angle and becomes a function of the separation between the film and the test scene, which in this system is fixed.

If a circular aperture were used in place of the slit, a blur circle would be introduced on the film plane. The larger the aperture used the larger the blur circle introduced to the system.

5.4 FABRICATION OF THE APERTURES

The blur was introduced to the targets by the aperture used in the blurring apparatus. It was therefore necessary to produce apertures which would introduce blur that represents real types of blur as described previously.

Circular apertures in the system would produce blur circles on the target. One dimensional linear motion was simulated by making a series of apertures with a constant height and the width twice that of the previous. Such a series is shown in figure 5.2.

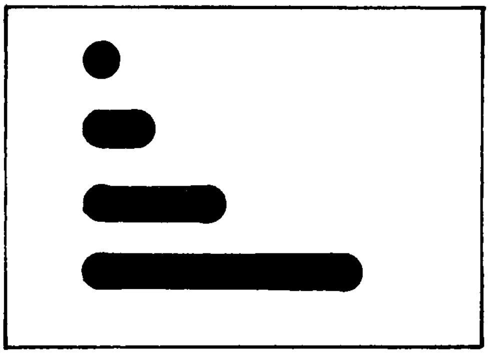


Figure 5.2 - One Dimensional Spreading

Dots from a transfer lettering sheet were placed on a clear acetate base. For the blur circle series, dots of increasing diameters were used. The one dimensional motion case was created using dots of the same diameter placed next to each other with the edges straightened by applying dashes from the transfer sheet where needed.

5.5 SENSITOMETRY

It is important to note that the illumination at the film plane in this system is a function of the aperture size and the transmittance of the test target. A pinhole will not have the same transmittance as a test scene and exposure corrections should be made to minimize the error introduced in the overall spread function of the system by differences in exposure. In cases where the aperture is extremely small, the incident illumination at the film plane will be limited causing long exposures. In these cases the exposures should be corrected for the reciprocity failure of the receiving film.

Kodak Plus-x film processed to a gamma of 1.0 was used to record the blurred targets.

5.6 CHOICE OF TARGETS

The resolution test target that was chosen was the Kodak Log Periodic Target. This target enables the Modulation Transfer Function (MTF) to be easily determined. This target has a bar width and spacing width such that the width of the n^{th} bar and space in the sequence are given by:[13]

$$\log_{10}(W_n) = \mathrm{Log}_{10} W_o - nC_2$$

where W_o and C_2 are constants. The target was produced on a lithographic film and mounted in a 35mm glass mount.

The pinhole was made in the same manner as the smallest blur circle aperture and shared its dimensions with a 0.5mm diameter.

Although never used due to difficulties which will be discussed later, a test scene was photographed on Plus-x pan film. The scene contained several obvious details to aid in the imaging evaluation.

CHAPTER VI

MAKING THE VAN DER LUGT FILTER

6.1 INTRODUCTION

The purpose of the holographic filter has already been discussed. In practice, there are many problems inherent in producing a quality hologram. These not only are present in making a Van der Lugt filter, but the Van der Lugt filter creates additional problems which will also be discussed in this chapter.

The Van der Lugt filter is made from the negative of the spread of the pinhole, made as described in chapter 5. The negative was produced by contact printing the positive onto the same film type (Plus-x) and processing in the same manner as the positive. The test scene and log periodic targets were also used as negatives to keep all targets at the same spread.

By placing the spread function in the optical system as the input, its Fourier transform was obtained in the back focal plane of the transform lens. A reference was added and the hologram was recorded on Kodak 649F spectroscopic plates.

6.2 DESCRIPTION OF APPARATUS

Figure 6.1 shows the optical system used for recording the Van der Lugt filter. The light source was a helium-neon laser with an output rated at 5 milliwatts. Helium-neon lasers put out a monochromatic illumination with a wavelength of 6328 Angstroms.

The spatial filter was a standard holographic accessory having a built in microscope objective and a pinhole approximately one micron in diameter. Allignment of the spatial filter is difficult at first, but with experience should pose no problem.

Both the collimator and Fourier transform lenses were Fuji lenses with focal lengths of approximately 250 mm. The diffraction patterns created by these lenses were checked under high magnification on an optical bench and were found to be of suitable optical quality. Lens holders had to be constructed. Their design is shown in appendix 5.

Allignment of the hologram is critical when it comes to reconstruction, so an x,y,z coordinate stage was used as the base for the plate holder. All apparatus was mounted on magnetic bases to fit a holographic table.

The table consisted of a heavy metal slab with tracks to help allign the elements. The tracks are not

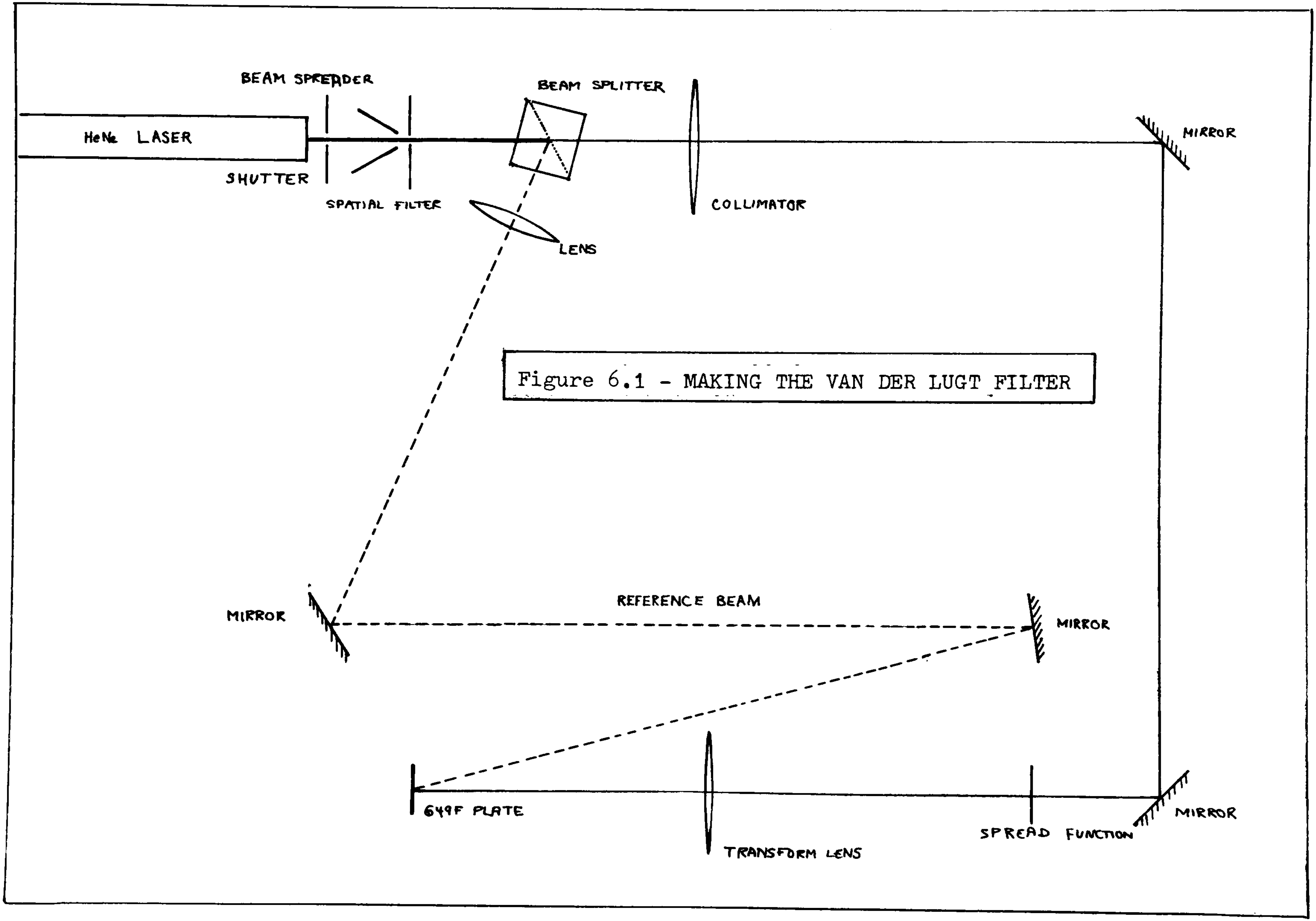


Figure 6.1 - MAKING THE VAN DER LUGT FILTER

necessary to the project. The table was isolated from the surrounding vibration by placing it on inflated inner tubes.

All mirrors used in the optical systems were front surface mirrors mounted solidly to the bases to prevent vibration.

6.3 RESOLUTION

When recording a hologram, the resolution of the film or plates used must be extremely high. The width of a bar in the interference pattern is given by

$$d = \frac{\lambda}{\sin \theta}$$

where d is the reciprocal of the frequency, λ is the wavelength of the incident illumination, and θ is the angle between the normal to the sensitized plate and the reference beam.

λ is 632.8 nm for a helium-neon laser. Typical values of θ would range from about 10° to 30°. Thus, the frequency of the interference pattern would range from about 275 to 800 cycles per millimeter. The light bar would be one half of each cycle requiring resolutions from 500 to 1600 lines/mm. Typically, θ was about 20° and called for a resolution of about 1000 lines/mm.

Kodak 649F plates were chosen to record the holograms since the resolution of this material is given at 2000 lines/mm, or a factor of twice what was required.

6.4 STABILITY

With typical resolutions as high as 1000 lines/mm, vibration in the system becomes critical. If the image vibrates relative to the film more than a quarter of a wavelength during the time of exposure, the contrast of the recorded hologram can be appreciably lowered and the hologram rendered useless. Several steps can be taken to insure against unwanted vibration.

Floating the system on inflated tires is a good way of insulating the system against vibration caused by people walking by the laboratory and other vibrations. The stability of this system can be checked by constructing a simple interferometer. Basically, this is a simple method for projecting the interference pattern created by the system on a wall or target. When the system is stable, the interference pattern is clearly visible as a pattern of alternating light and dark bands. When unstable, the bands disappear at the slightest vibration. The optical system for a simple interferometer is shown in figure 6.2.

The interferometer only checks the stability of the system as a whole and will not usually demonstrate

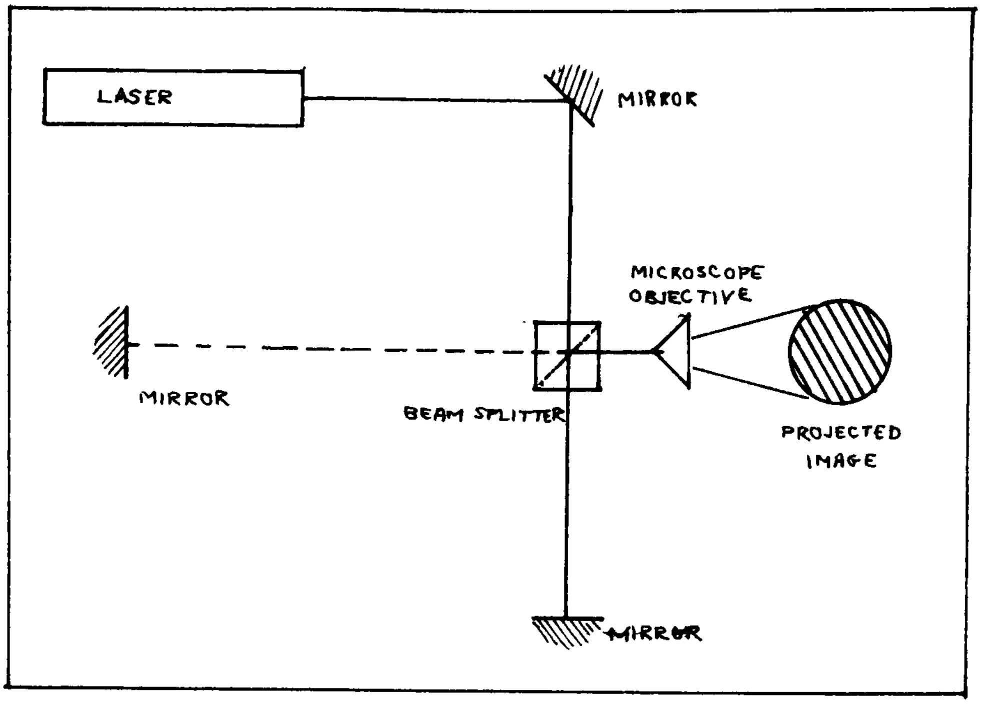


Figure 6.2 - Interferometer

instability of the system components. Mirrors which may vibrate in their holders or components insufficiently attached to the optical table are frequent causes of vibration. The best way to check for this type of vibration is by placing a high power microscope in the Fourier plane. Using this method, the interference pattern is clearly visible, but the slightest vibration will make it undetectable. Tapping of the components in the system, one at a time, will make the interference pattern disappear. If the component is stable, however, the interference pattern should reappear instantly. The longer it takes the pattern to reappear, the less stable that element is.

6.5 SENSITOMETRY

As described earlier, the optical processor requires that the film be processed to a precise gamma of 2. To determine the proper development procedure, sensitometric tests were conducted on the 649F plates. The set-up is shown in figure 6.3.

To make the sensitometry as accurate as possible, the exposures were made with the laser source which would be used for exposing the plates when making the filter. The laser beam was spread and spatially filtered as described for exposing the plates. A Kodak #2 neutral step tablet was placed on the plate and was then processed in Kodak D-19 mixed as specified in appendix 3.

A development time of two minutes was shown to give the necessary gamma at 72° F. Appendix 3 gives details of the processing formulations and their times.

A CdS cell was attached to an ohm meter which was then calibrated using the inverse square law to obtain a calibration curve. The meter and method of calibration is described more fully in appendix 4.

To insure the best possible hologram, a series of exposures was made on each plate in one f-stop increments bracketing around the measure exposure.

6.6 THE BEAM RATIO

As described earlier, the proper beam ratio plays

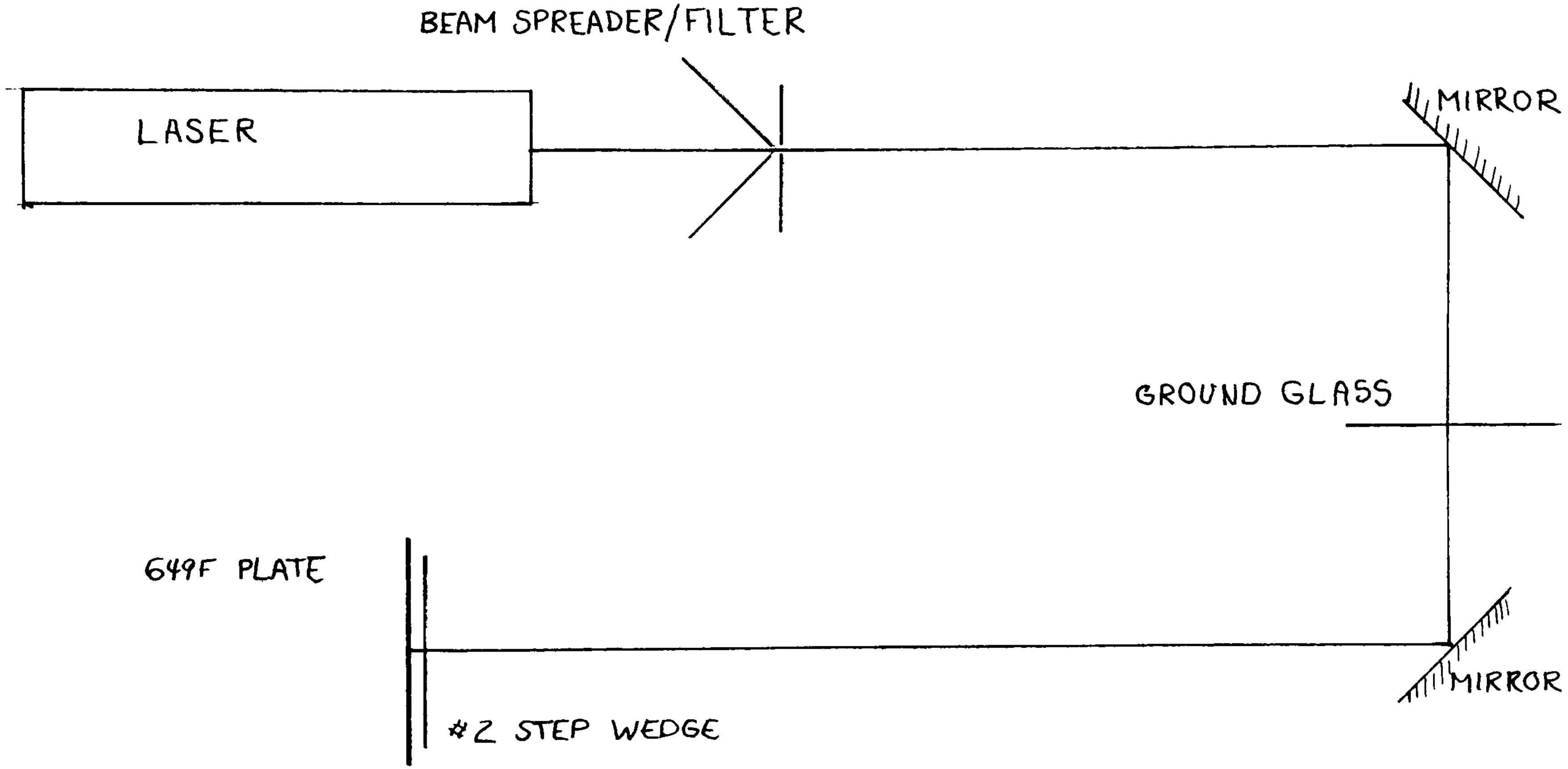


Figure 6.3 - SENSITOMETRIC TESTING

an important part in the proper recording of the hologram. The Van der Lugt filter poses a particular difficulty in this respect.

Both the reference and the object beams are coming from the same source through a beam splitter. The reference beam must be spread to cover the entire transform while the object beam is essentially brought to a focus. The intensity of the object beam at the center of the transform is extremely high. It is difficult to attain a beam ratio where the reference beam must be more intense than the object beam. It must also be noted that the beam ratio is continually changing as the intensity of the transform drops off severely as the distance from the center increases.

The best beam ratio was found by using a lens after the beam splitter to refocus the reference beam so that it just covers the transform on the photographic plate. A microscope was inserted in the Fourier plane and neutral density filters inserted in the reference beam until the best contrast of the fringe pattern was observed. It was found that when the Airy disc is just visible under the microscope within the interference pattern, the best hologram was obtained.

CHAPTER VII

IMAGE ENHANCEMENT

7.1 DESCRIPTION OF APPARATUS

The optical system used for the actual filtering is shown in figure 7.1. The hologram has been inverted to direct the beam carrying the convolution information back toward the center of the optical table. The lens used for retransforming the image is identical to the first transform lens. All other optical components are the same as described for making the Van der Lugt filter.

7.2 ALLIGNMENT OF THE FILTER

The most difficult thing about the reconstruction step is the allignment of the Van der Lugt filter in the Fourier plane. This problem could be minimized by developing the filter in a liquid gate, never removing it from its original location.

Without the gate, the filter must be accurately replaced in exactly the same position it was in when being exposed. The x,y,x coordinate stage allowed for such reallignment of the filter.

When the filter is properly alligned, three distinct beams can be seen emerging from the hologram. The best possible allignment is obtained when these beams are

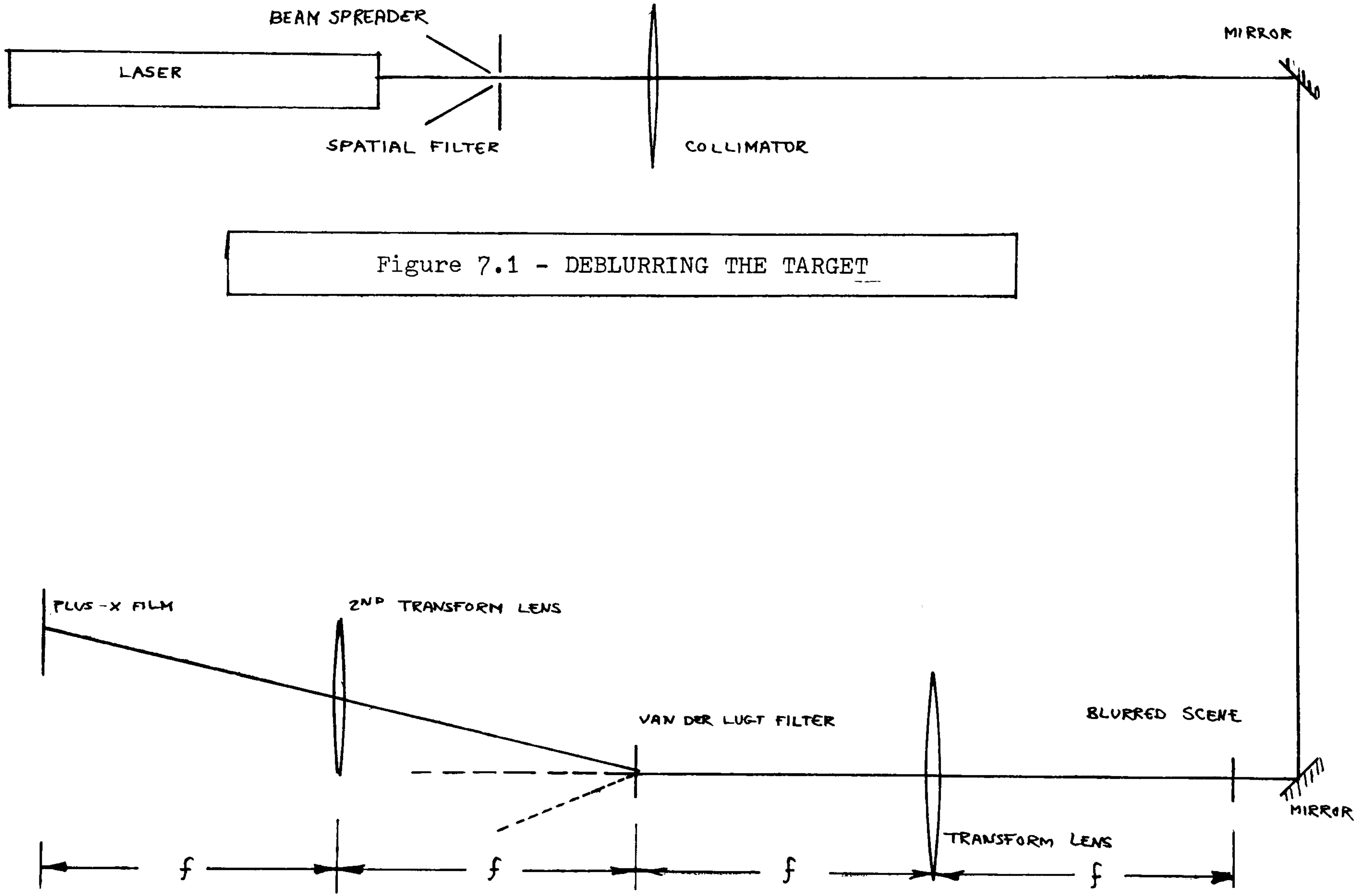


Figure 7.1 - DEBLURRING THE TARGET

darkened by the amplitude information on the filter.

The reconstructed image is dim and difficult to judge visually. It is best judged when all ambient light in the laboratory is removed. The corrected image was recorded on Plus-x with typical exposure of several seconds. The Plus-x was processed identically to the blurred images to keep all factors, except those from the actual deblurring, constant.

CHAPTER VIII

IMAGE EVALUATION

8.1 METHOD

The criteria for judging image quality of the blurred and deblurred log periodic test targets was the modulation transfer function. This allowed a comparison of the image quality at various spatial frequencies.

The MTF was derived from the samples by scanning the bar images with a microdensitometer. A narrow but long slit (1.2 um X 150 um) was used to effectively measure the smallest bars and yet keep the resulting noise low enough so as to make an intelligible trace. The scan speed of the targets was kept low at 4mm/minute in order to get a trace that was spread over a greater distance on the chart recorder. The frequency of a particular bar and space combination was obtained off the trace by taking the reciprocal of the period. For each frequency, the average high and low density was obtained. The MTF for the lowest frequency was given a value of 1.0 and all other MTF's were obtained by dividing the density difference for the wanted frequency by the density difference for the lowest frequency (2.5 c/mm). This normalized all the data against the lowest frequency. The data was plotted with frequency on the horizontal axis and MTF on the vertical axis.

To compare the quality of the deblurred target with the blurred target, a comparison was made by visual examination of the modulation transfer factors off the graphs. This enabled a check to see if indeed the enhanced image was better than the blurred target and if so, at what frequencies.

8.2 APPARATUS

An Ansco model IV microdensitometer was used to make the scans of the image. Two 10X influx and efflux objectives with a slit to give an effective aperture of 1.2 X 150 microns were used. The chart recorder was fixed at 2 inches/minute and the scan speed was 4mm/min.

CHAPTER IX

RESULTS

9.1 RESULTS

As shown in figure 9.1, the deblurred image is indeed improved over the blurred image. Both images show an MTF of 1.0 out to about 3 c/mm where the image then starts to be degraded. The blurred image, however, falls off more rapidly at this point. The enhanced image has a higher MTF value for similar frequencies to about 10c/mm. The greatest MTF difference is at the 6c/mm level. Here the enhanced image records about 0.8 MTF and the blurred image about 0.5 MTF. This corresponds to a maximum gain in MTF by 60%.

9.2 DISCUSSION

To the eye, the enhanced image does look sharper while the blurred image appears soft. However, the enhanced image has the familiar laser speckle and sharp but ragged edges. This is unpleasing to the eye but does have the appearance of being sharper.

A slight gain in MTF is realized by the deblurring process. This gain occurs between 3 an 10 c/mm. Beyond 10 c/mm, although not tested, it appears that the blurred image has a higher MTF than the enhanced and falls off more gradually at this point.

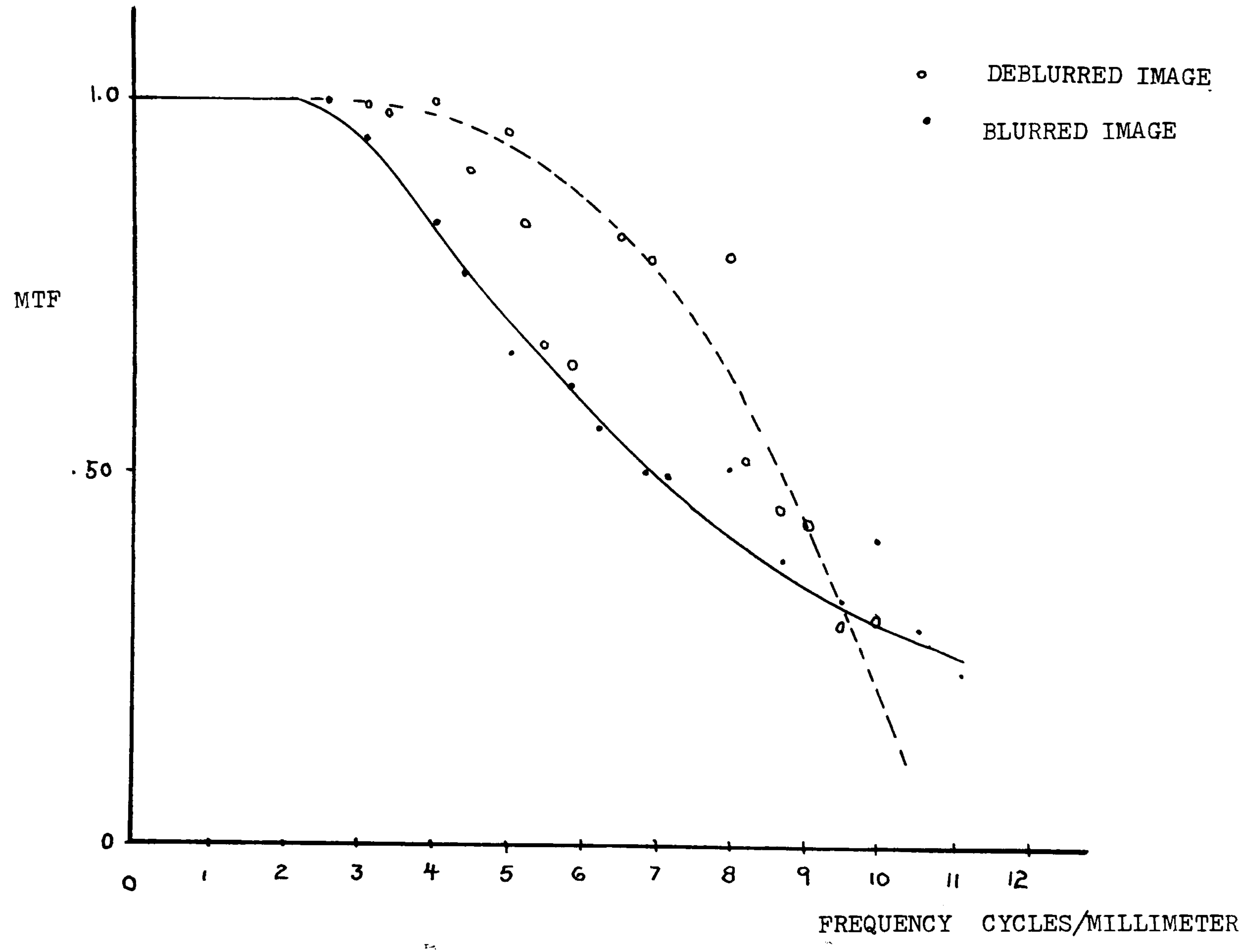


Figure 9.1 - MODULATION TRANSFER FUNCTIONS

CHAPTER X

CONCLUSIONS

10.1 CONCLUSIONS

The process of deblurring has been shown to work in theory and practice. However, in practice, the maximum increase in MTF value obtained was 60% higher at 6c/mm. The enhancement only appears at low frequencies under 10c/mm and beyond this the MTF approaches zero quickly. Since sharpness is subjectively measured by the eye and is a low frequency response, the enhancement could prove particularly valuable to images that need to be evaluated by the eye. The high frequencies don't appear to be enhanced and to the eye the bar patterns were broken up and could not be discerned. Photographs that are eventually to be used for data analysis with much high frequency information would not benefit from this deblurring process.

The process itself is not practical on a mass production scale. The allignment of the Van der Lugt filter is very critical and is hard to achieve physically. The process would definitely have to be limited to high priority subjects. Exposure times are long with all but very powerful lasers and the stability requirements keep the system in a laboratory.

10.2 RECOMMENDATIONS FOR FUTURE STUDY

The enhancement process was found to improve image quality a maximum of 60% in terms of MTF. Future study could see what kind of sharpness increase can be obtained using actual photographs instead of the log periodic target.

Also, it would be desirable if a system could be devised where the appropriate Van der Lugt filters oould be made ahead of time and then just dialed into the Fourier plane until the best visual sharpness was seen at the reconstruction end. This would take considerable time in making the filters, but would allow for the best sharpness to be obtained in the deblurring process.

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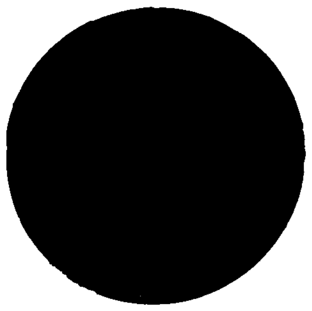
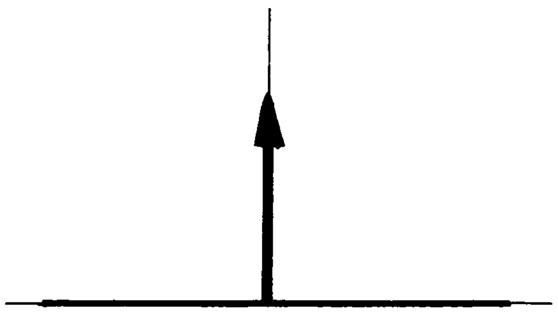
APPENDIX I

PICTORAL DESCRIPTIONS OF SOME OBJECTS AND THEIR TRANSFORMS

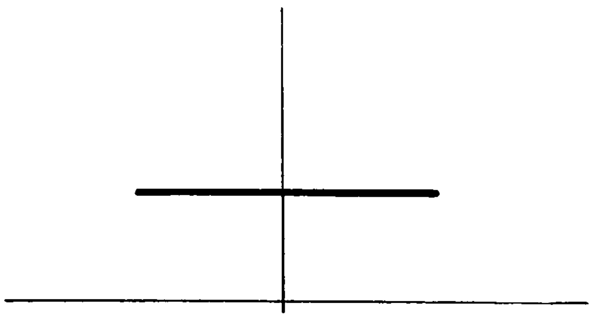
POINT



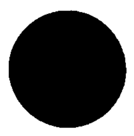
TRANSFORM OF POINT



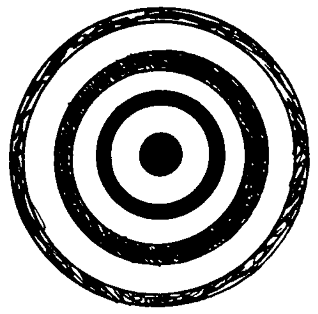
GRAPHICAL REPRESENTATION: DELTA FUNCTION



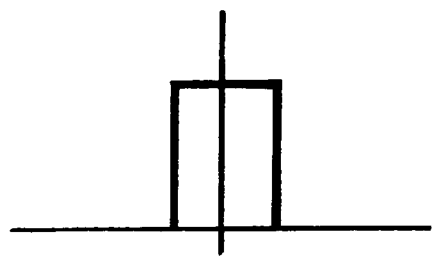
FOURIER TRANSFORM



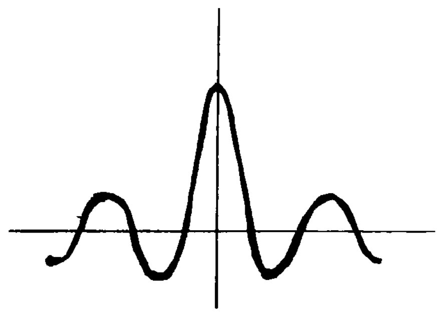
BLUR CIRCLE



TRANSFORM: AIRY DISK



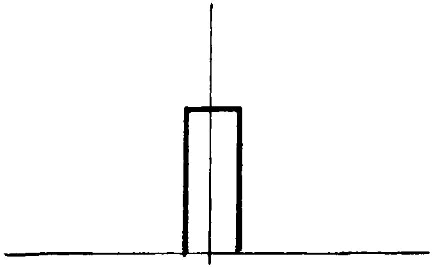
GRAPHICAL REPRESENTATION OF BLUR CIRCLE



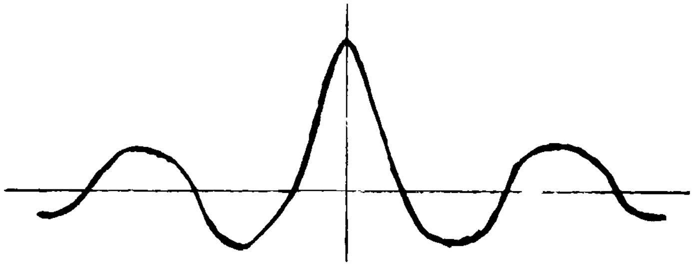
FOURIER TRANSFORM

SPREAD TO REPRESENT LINEAR MOTION

AMPLITUDE SPECTRUM



GRAPHICAL REPRESENTATION OF SPREAD



FOURIER TRANSFORM

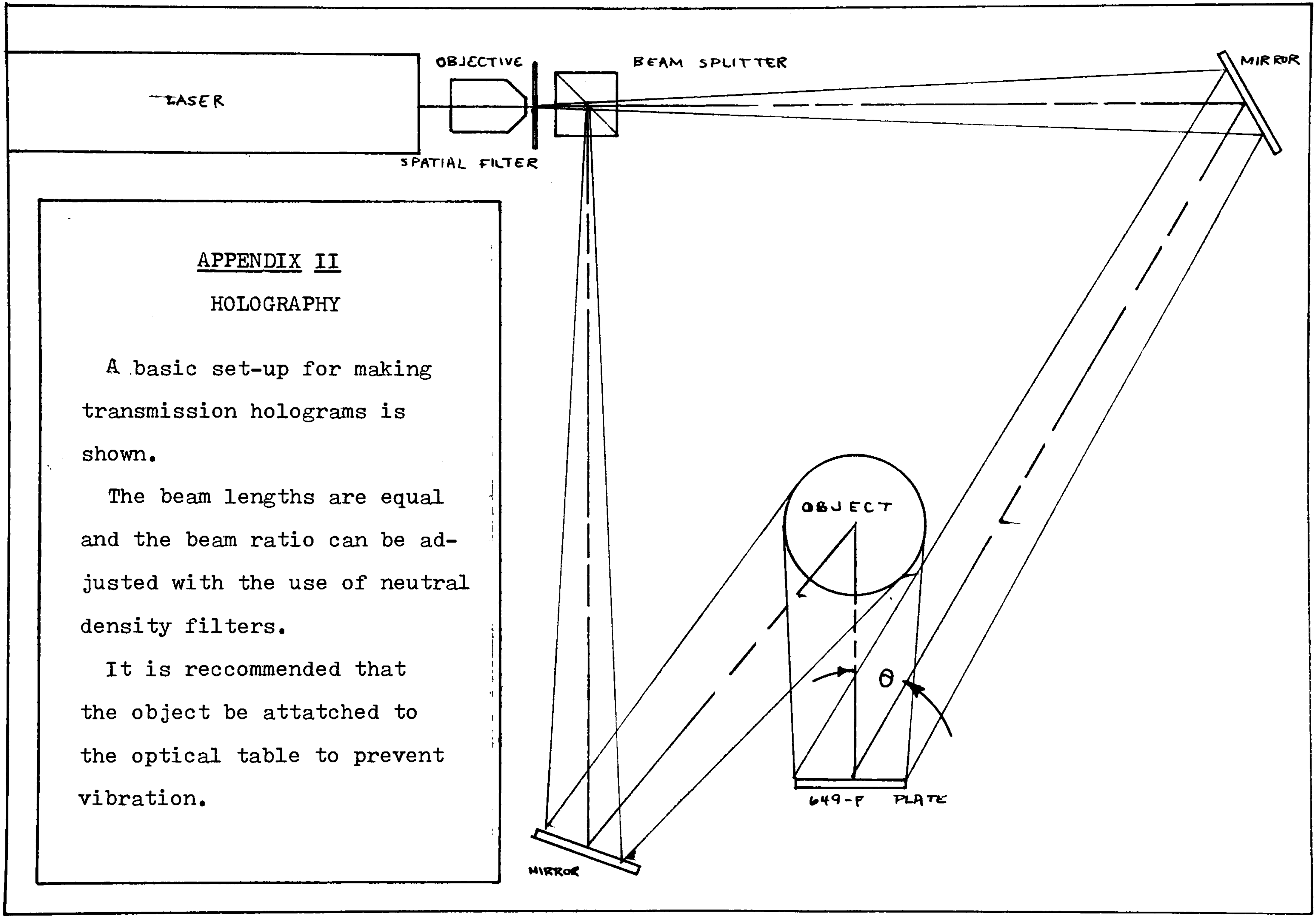
APPENDIX II

HOLOGRAPHY

A basic set-up for making transmission holograms is shown.

The beam lengths are equal and the beam ratio can be adjusted with the use of neutral density filters.

It is reccommended that the object be attatched to the optical table to prevent vibration.



APPENDIX III

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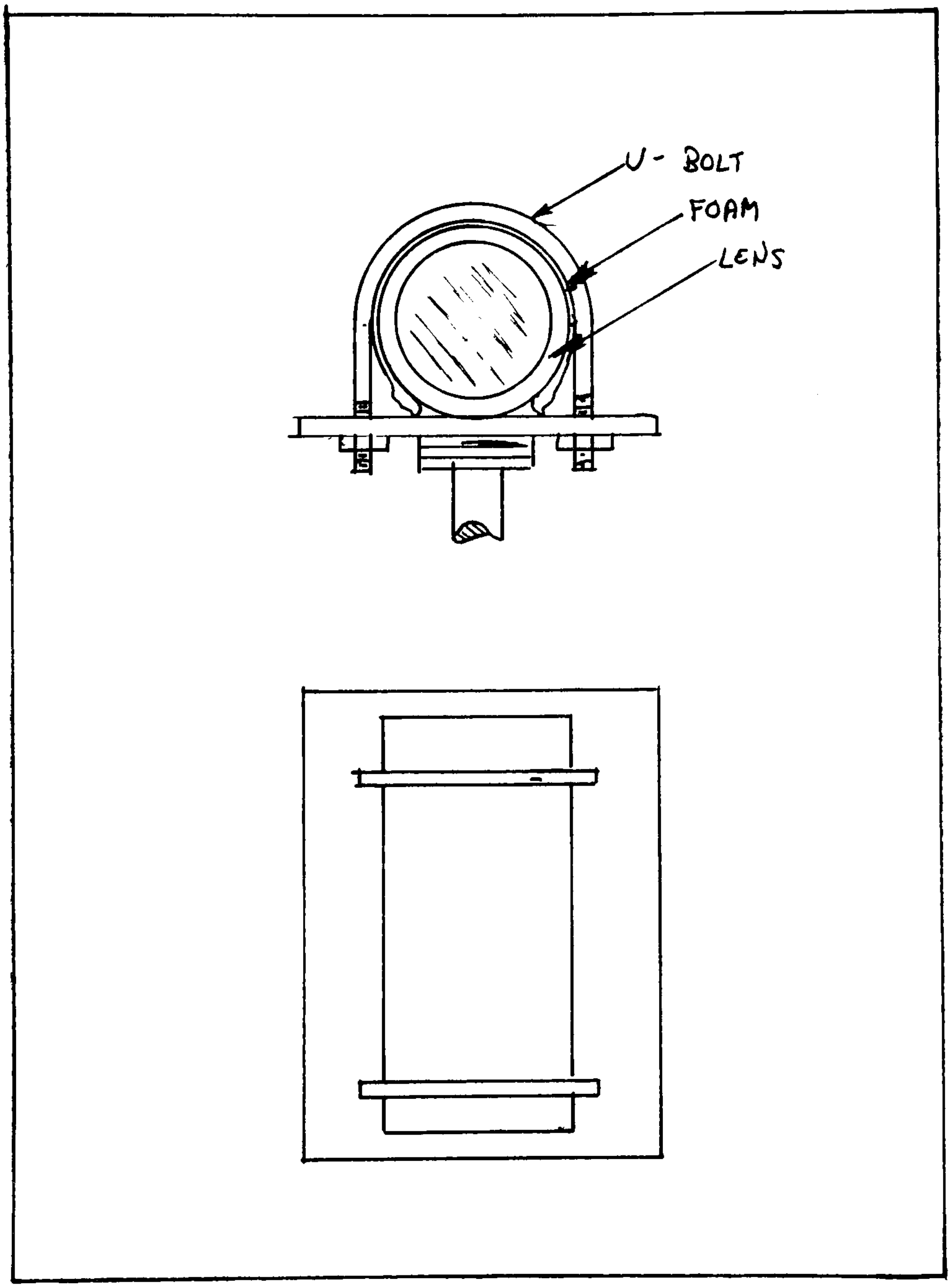
The Kodak 649F Spectroscopic plates were processed for 2 minutes at 72° F ± 0.5° F using a tray with tray rock agitation. This gave a gamma of 2.0. D-19 developer was used and was prepared with distilled water. A water rinse for 10 seconds followed and finally the plates were fixed for 5 minutes in Kodak F-5 fixer. Wash times of 10 minutes and hot air drying followed.

The Kodak Plus-x sheet film was developed in HC-110 dilution B (1:31) for 20 minutes at 72°F. Tray processing and agitation as well as the same fix and wash as for the plates followed. A gamma of 1.0 was obtained with this procedure.

APPENDIX IV SPECIALLY CONSTRUCTED APPARATUS

1. The Fuji lenses used in the optical processor had to be mounted into the optical system. A plexiglass platform was constructed and the lens mounted as shown in the figure below.

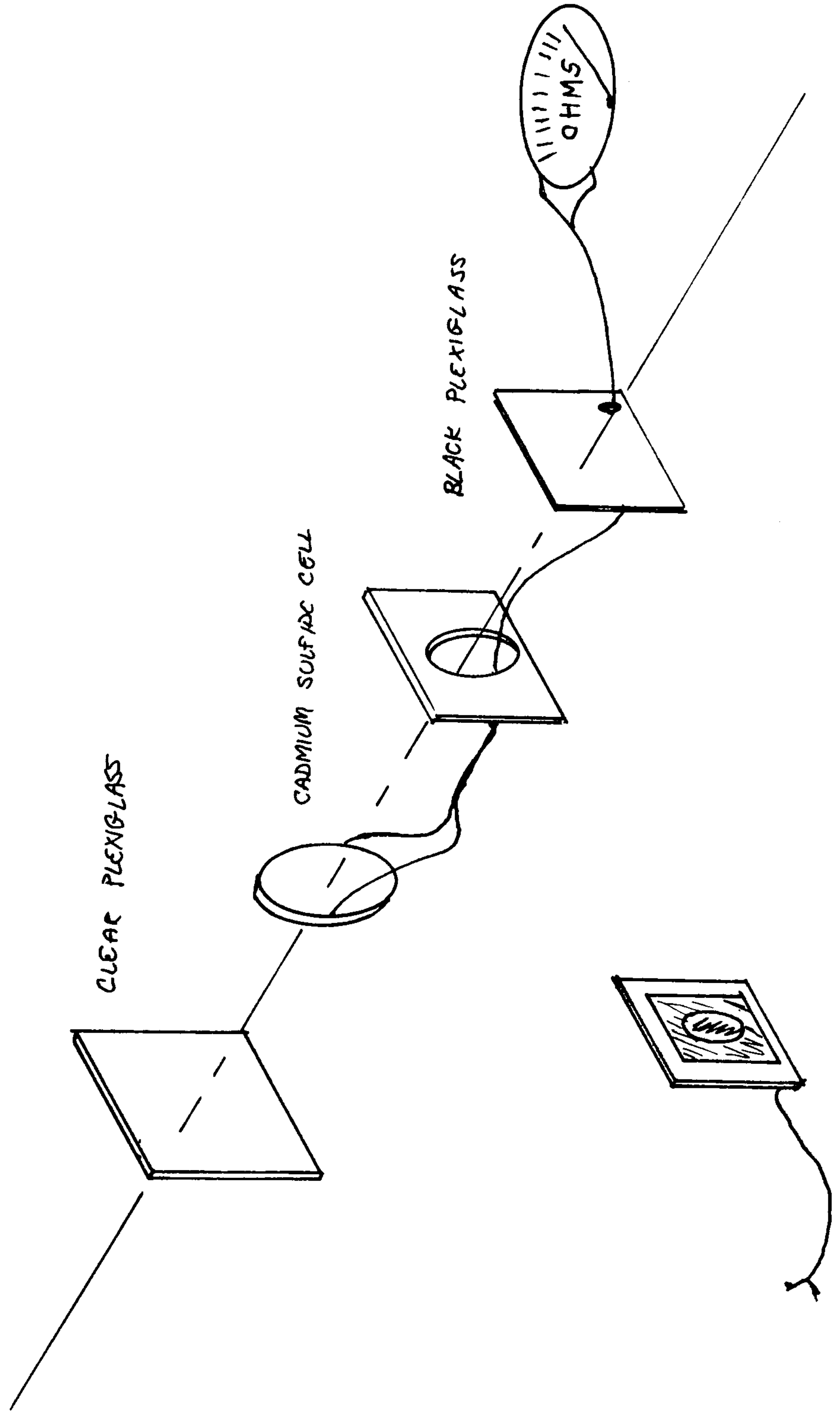


2. A luminance meter was constructed by moutning a cadmium sulfide cell as shown in the figure on the following page.

The cell was connected to an ohm meter and then calibrated on an optical bench using the inverse square law.

The conversion factor from ohms to microwatts/cm^2 was determined by measuring the output of a laser on a calibrated meter, then measuring the resistance. It was found that

$$40 \text{ uW/cm}^2 = 500\Omega$$


CLEAR PLEXIGLASS
CADMIUM SULFIDE CELL
BLACK PLEXIGLASS
OHMS