

AN OPTICAL/DIGITAL INCOHERENT IMAGE PROCESSING SYSTEM  
FOR AN EXTENDED DEPTH OF FIELD

by

Masoud Motamedi

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APPROVED:

---

Dr. T. C. Poon

---

Dr. K. B. Yu

---

Dr. G. J. Indebetouw

---

Dr. R. O. Claus

April, 1985  
Blacksburg, Virginia

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## Chapter I

### INTRODUCTION

The disturbing effects of defocusing on image formation in optical systems is well known, and efforts have been made to reduce its amount in design and production of optical instruments. In practice, however, many technical difficulties have to be surmounted and as a rule one has to be contented with some mis-focus.

A real time system, that can be applied whenever depth of focus is a serious limitation, is needed. Such a system can be used in applications such as large area of measure, situations where focal plane tolerance cannot be held, and remote photography, where focusing is impractical or distance to object cannot be estimated.

To design a real time system, an optical system can be regarded as a linear filter of spatial frequencies. It has been argued that if one knows the optical transfer function (OTF) of a degraded optical system, then a compensating filter could be obtained to correct degradation due to the imaging process. The most obvious means of constructing a compensating filter is by multiplying the transfer function of the degraded system by its inverse function so that the resultant filtering effect is that of unity gain.

However, certain image degrading optical transfer functions, such as the OTF of an out of focus system, can become negative, thereby possessing some zero crossings which cannot be inverted. The corrected image, in this case, will be lacking in components at frequencies in which the transfer function becomes zero and will become more or less different from the original object. Hence the correction cannot be perfect.

The optical transfer function can be used to characterize the transfer properties of an optical system; the two necessary conditions on the focused image appear to be that the OTF must be:

- (1) a monotonically decreasing function, and
- (2) non-negative.

In studying the transfer function of an out of focus image, however, it appears that there are a number of zero-crossings which makes it impossible, as was mentioned before, to reconstruct a perfect image by inverse filtering. Also, the transfer function for high frequencies becomes low in value and sometimes phase changes occur at some frequencies, thus impairing the image.

Throughout the years, different methods have been considered to reduce the amount of mis-focus. In 1971 Mino and Okano studied the effect of two different shaded

apertures on a defocused system[1]. They showed that, when a system is out of focus, an aperture of the type in which the amplitude transmittance decreases gradually from the center of the pupil toward its rim, yields an improved defocused image that is faithful to the outline of the object. However, the second type, in which the amplitude transmittance decreases from its rim toward the center, does not show an improved image.

In 1972, Hausler introduced a two-step method to increase the depth of field[2]. He first indicated that the transfer function of an out of focus system has isolated zeros, in contrast to the transfer function of an in focus system which, as seen in Fig. 1.1(a), is always positive. In the first step of this method, the objective moved along the optical axis through a distance somewhat longer than the object thickness, thereby integrating the image in time. The integration would therefore get rid of the zeros of the out of focus transfer function as seen from Fig. 1.1(b). However, the method will cause an attenuation of high frequency components. This attenuation can be compensated for by using a post detection filter of the form shown in Fig. 1.1(c), where the filtering is done by conventional coherent image processing methods.

Five years later, in 1977, Hausler and Lohmann used the

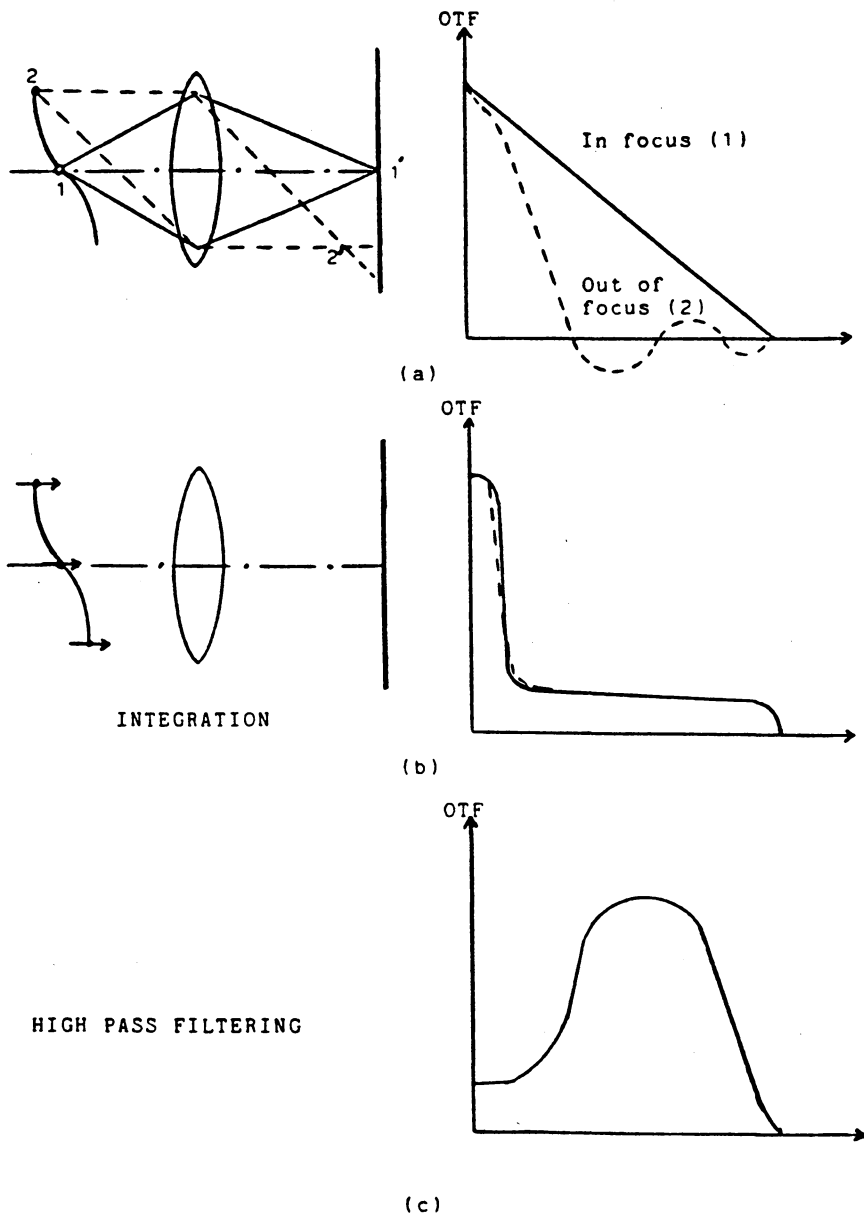


FIGURE 1.1: Principle of the increased depth of focus as used by Hausler and Lohmann[2].

method described above in a hybrid optical/electronic system[3]. The object was again vibrated rapidly in front of a vidicon camera, and the video output was highpass filtered by the use of electronic circuitry.

The use of Fresnel zone plates, to extend the depth of field of an incoherent imaging system, was studied by Indebetouw and Bai in 1984 [4]. It was shown that if the Fresnel zone plates are used as pupil apertures, the depth of field will be extended without reducing excessively image intensity and contrast.

The use of an annular aperture has not received much practical consideration in the past. In 1952, the effects of central obstruction of the aperture, i.e., the effects of the annular aperture, on the three-dimensional light distribution near the focus of an aberration-free optical system were considered by Linfoot and Wolf[5]. They showed that when the central obstruction is large, the bright central nucleus becomes longer and narrower so that focal depth and resolving power of the optical system are both increased. This led to the study of the annular aperture by Welford in 1960, where he theoretically showed the increase of the depth of field of a photographic objective by using an annular aperture[6]. In 1971, the first practical system which used an annular aperture to increase

the depth of field was considered by Mc Crickerd[7]. It was shown that annular apertures of high aspect ratios can be used with coherent image processing to reduce the effects of spherical aberrations, field curvature, and longitudinal chromatic aberration; and to extend the depth of field. However, the system studied is only practical for small field imagery in non-real time.

In 1984, Motamedi, Poon, and Yu proposed a hybrid optical/digital incoherent image processing system. It was indicated that the isolated zeros in the optical transfer function of the defocused system can all be avoided by choosing an annular aperture with a proper radius ratio, however, in the process of increasing the depth of focus of the system, this method results in a loss of image contrast. This loss of contrast can be restored by using a computer-generated annular pass filter. This thesis involves the study of this proposed system. The theory, design, and results of the system are considered.

In chapter II the depth of field and the depth of focus for a single lens system and for a multi-lens system are studied. The theory behind the increase of the depth of field by using the annular aperture is discussed and its effect on the contrast of the image and the method to compensate for it are explained.

Chapter III is a review of the discrete Fourier transform, spatial filtering, and their use as applied to this research.

Chapter IV discusses a general optical/digital system in which incoherent systems are considered. It is shown that a hybrid optical/digital system can be divided into an optical, a digital, and an interface subsystems. These systems are considered individually for their application to the incoherent optical/digital image processing system.

The results of the experiments done are given in chapter V. It is shown that the proposed method works with some loss of contrast, however, it is believed that with better digital filtering techniques the remaining loss can be compensated. The conclusion and future research on the system are presented in chapter VI.

Finally, the appendices contain the computer programs used, and various experimental procedures that seem obvious in retrospect, but are actually a result of many problems encountered during the experimental phases of this work. They are intended as future reference as this research progresses in hopes that repetition of this work may be avoided.

## Chapter II

### OPTICAL THEORY AND ANNULAR APERTURE

The study of the effects of the annular apertures on an optical system requires a prior knowledge of optical lenses and their depths of field and focus. The two terms "depth of field" and "depth of focus" are liable to be confused, and they are generally defined in the following manner. The depth of focus of a lens is the distance along the lens axis in the image space from the plane of sharp definition to the place where the image of the point source just reaches a detectable out of focusness as seen by an average observer[9]. Similarly, the depth of field is the corresponding distance in the object space.

The theory of optical lenses is first considered, and then the effects of increase of the depth of field, by the use of an annular aperture, are considered.

#### 2.1 Optical Lenses

A lens is defined as a combination of two surfaces that enclose a medium of a refractive index different from that of the outside of the surfaces. A lens is considered thin if its thickness is much less than the radii of curvature of its two surfaces. However, if the thickness is by no means

negligible, the lens is considered a thick lens; any optical system consisting of a number of simple lenses can also be considered as a thick lens[10].

In every optical system, using thin lenses or thick lenses, the bundle of light passing through is limited in cross section, either by the finite size of the lenses or by additional diaphragms called aperture stops(Fig. 2.1). A lens that is too small will reduce the efficiency of others. A lens that is too large is wasteful. Therefore, the proper design of any system requires that the diameters of the various lenses are correctly chosen[11].

Consider all the rays from the axial point  $P_o$  as shown in Fig. 2.2. The stop which determines the cross-section of the image-forming ray is called the aperture stop or A.S. for short. Aperture stop can be considered as the physical diameter which limits the size of the cone of radiation which an optical system will accept from the axial point on the object. The image of the aperture stop as seen from the object is called the entrance pupil, which is identical to the A.S. if it lies in front of the first surface. The angle  $2\theta_o$  which the diameter of the entrance pupil subtends at  $P_o$  is called the angular aperture[12]. The image of the aperture stop formed by the part of the system which follows it is known as the exit pupil; the angle  $2\theta_i$  which its

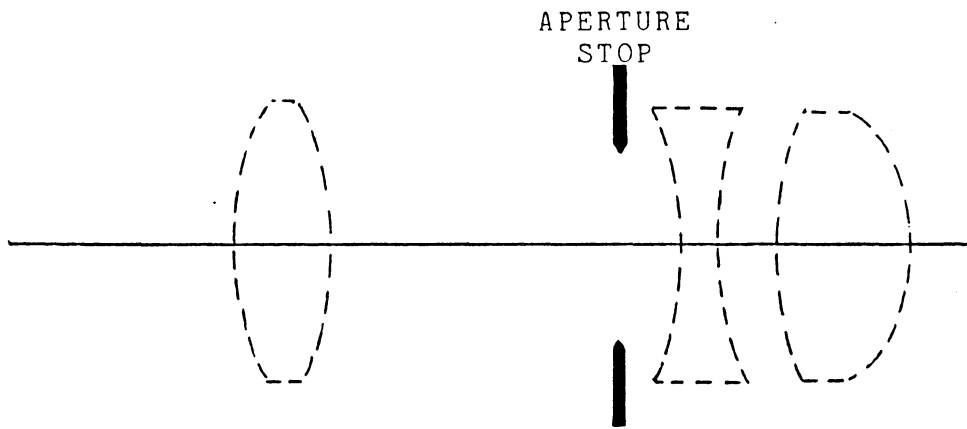


FIGURE 2.1: Aperture Stop placed in a three-element lens system

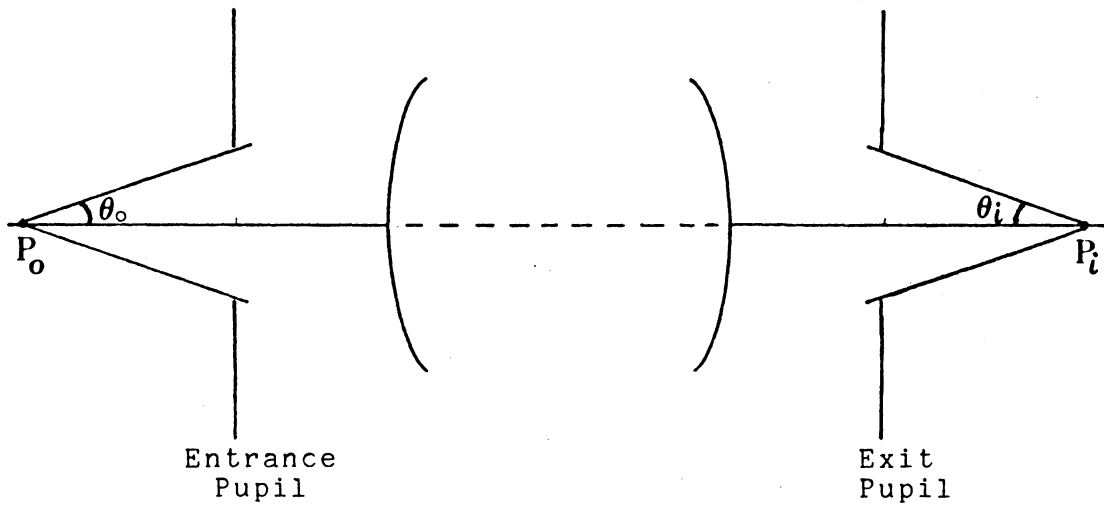


FIGURE 2.2: Stops and pupils

diameter subtends at the image  $P_i$  is called the projection angle[12].

When one considers a single-lens system with plane waves of light incidence, a convenient measure of its light-gathering power is the so called "F-number". It is the ratio of the focal length of the system to the diameter  $D$  of the entrance pupil:

$$F = f/D. \quad (2.1)$$

The entrance pupil, exit pupil, and F number along with the individual characteristics of thin and thick lenses will be considered seperately.

### 2.1.1 Thin lenses

A thin lens, as was mentioned before, is a lens that its thickness can be neglected. If one knows the location of an object in relation to the lens, there are three known rays that can be drawn, any two of which are sufficient to locate the image:

- (a) a ray from the top of the object entering parallel to the axis, which passes through the focal point on the other side of the lens;
- (b) a ray from the top of the object entering through the front focal point and emerging parrallel to the axis on the other side of the lens;
- (c) a ray entering through the center of the lens and

emerging at the same slope.

These three rays along with the image formed are shown in Fig. 2.3.

It should be mentioned that the focal length of the lens is given by:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad (2.2)$$

where, from Fig. 2.3:

$f$  is the focal length,

$p$  is the distance of the object from the lens, and

$q$  is the distance of the image from the lens.

This equation can be used in locating the formed image if the focal length and the distance from the object to the lens are known.

The size of the image depends directly on the size of the object by a factor  $M_T$  known as the lateral or transverse magnification.  $M_T$  is given by:

$$M_T = \frac{h_i}{h_o} \quad (2.3)$$

where  $h_o$  and  $h_i$  are the object height and the image height, respectively. From similar triangles in Fig. 2.3,

$$\frac{h_o}{p} = \frac{h_i}{q},$$

and thus,

$$M_T = \frac{q}{p} \quad (2.4)$$

There are two methods of introducing an aperture stop in a single lens system; in front of the lens or in the back

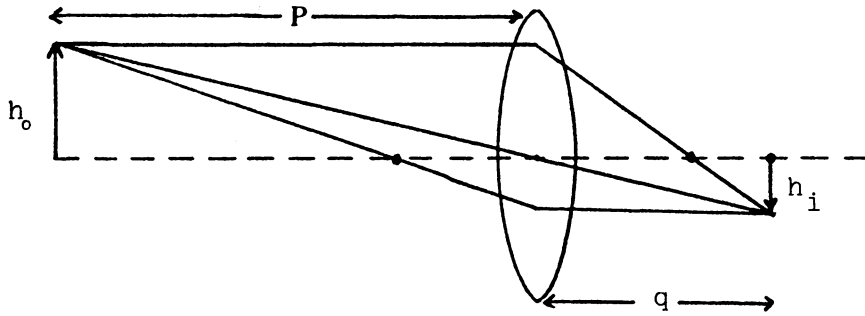


FIGURE 2.3: Image formation of a thin lens.

of the lens. Following the definition of the A.S., if there are no lenses between the object and the A.S., the latter itself serves as the entrance pupil. To illustrate the point examine Fig. 2.4, which is a lens with a front aperture stop. Since there are no lenses between the object and the aperture stop, the A.S. serves as the entrance pupil. In contrast, the exit pupil is the image of the A.S. as seen from an axial point on the image plane through the interposed lenses. In Fig. 2.4 the image of the A.S., as seen from an axial point on the image, is virtual and magnified. It can be located by sending a few rays from an axial point on the image, out from the edges of the aperture stop. Notice that all of this just means that the cone of light actually entering the optical system is determined by the entrance pupil, while the cone leaving it is controlled by the exit pupil.

In the imaging system shown in Fig. 2.4, we can define an effective F-number ( $F_{\text{eff}}$ ), given by:

$$F_{\text{eff.}} = \frac{q}{D} , \quad (2.5)$$

where  $D$  is the diameter of the entrance pupil of the system.

The knowledge of the theory behind the single lens can lead to the study of the depth of focus and the depth of field of this system. Consider the single lens shown in

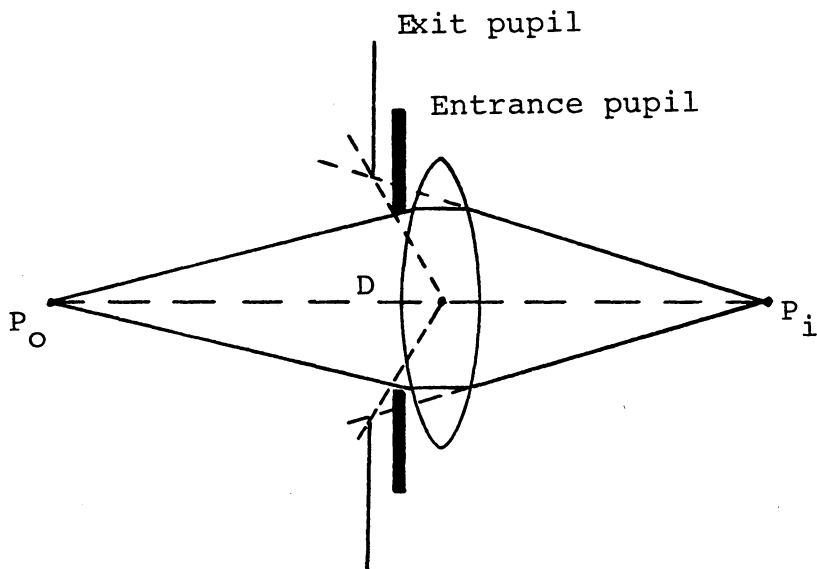


FIGURE 2.4: Entrance and Exit pupils.

Fig. 2.5. It is desired to first find a relationship between the depth of focus and the depth of field of the lens, and then find an expression for the depth of focus.

If the original distance of the object from the lens is denoted by  $p$ , the depth of field by  $\Delta p$ , the distance of the image from the lens by  $q$ , the depth of focus by  $\Delta z$ , and the effective diameter of the lens by  $D$ , then from (2.2):

$$\frac{1}{p} = \frac{1}{f} - \frac{1}{q} = \frac{(q - f)}{fq} . \quad (2.6)$$

Similarly,

$$\frac{1}{p + \Delta p} = \frac{1}{f} - \frac{1}{q - \Delta z} = \frac{q - \Delta z - f}{f(q - \Delta z)} , \quad (2.7)$$

or, after some algebraic simplification, the depth of field will be given by:

$$p = \frac{f^2 \Delta z}{(q - f)(q - f - \Delta z)} . \quad (2.8)$$

From (2.6),

$$q - f = \frac{fq}{p} , \quad (2.9)$$

and, from (2.4),

$$\frac{q}{p} = M_T = M. \quad (2.10)$$

Therefore, (2.8) can be rewritten as:

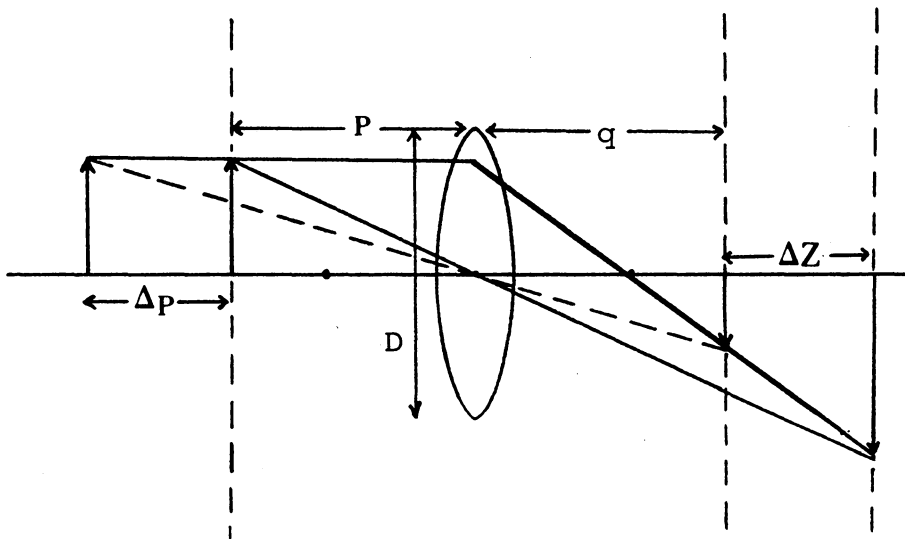


FIGURE 2.5: Depth of field and depth of focus of a single lens.

$$\Delta p = \frac{f^2 \Delta Z}{f^2 M^2 - fM\Delta Z} . \quad (2.11)$$

Approximating that  $fM \gg \Delta Z$  ,  $\Delta p$  can be given by:

$$\Delta p = \frac{\Delta Z}{M^2} , \quad (2.12)$$

or, the depth of field is approximately equal to the depth of focus divided by the square of the magnification of the system.

The problem now changes to finding an expression for the depth of focus,  $\Delta Z$  , in terms of the known quantities of the system, or quantities that can easily be measured. Since the depth of focus depends on the uncertainty of the observation of the image formed, the Heisenberg uncertainty principle can be used.

If one considers Einstein's photon theory, that is the energy of a light beam traveling through space in concentrated bundles called photons, then the energy  $E$  of a single photon is given by[13]:

$$E = h \nu , \quad (2.12)$$

where  $h$  is the Plank's constant, and  $\nu$  is the oscillation frequency. Using this theory, consider the two beams of photons moving from left to right in Fig. 2.6. The first

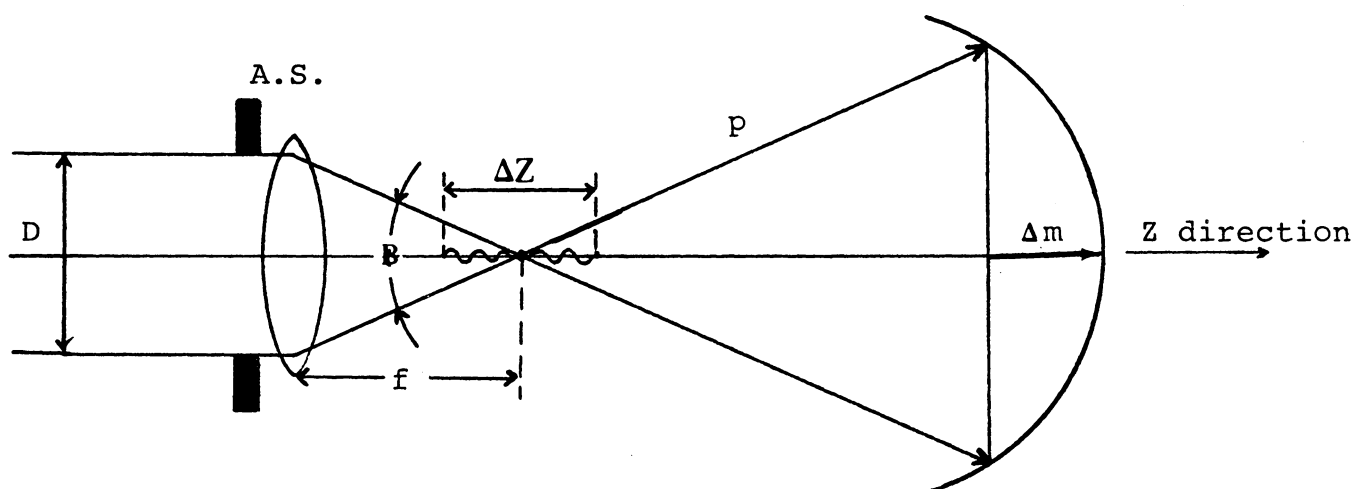


FIGURE 2.6: Uncertainty principle used in finding depth of focus.

beam of photons is the one that can get through the upper most point of the aperture stop, where the A.S. is put right in front of the lens for simplicity. The second beam considered is the one passing through the center. The beams are assumed to originate at a great distance away from the lens; thus all the two beams will meet at the focal point in the back of the lens. There is, however, an uncertainty in the position of the focal point, denoted by  $\Delta z$ , due to the difference in momentum between the two beams along the Z-direction.

The momentum of a photon is given by:

$$m = \frac{h}{\lambda} , \quad (2.13)$$

where  $\lambda$  is the wavelength of the light.

Based on the Heisenberg uncertainty principle, we have[14],

$$\Delta m \Delta z = h , \quad (2.14)$$

or,

$$\Delta z = \frac{h}{\Delta m} . \quad (2.15)$$

From Figure 2.6, the uncertainty in momentum can be written as:

$$\Delta m = m - \frac{h}{\lambda} \cos(B/2) . \quad (2.16)$$

Substituting (2.13) in (2.16) and then into (2.15):

$$\Delta z = \frac{\lambda}{1 - \cos(B/2)} , \quad (2.17)$$

which can be rewritten as:

$$\Delta z = \frac{\lambda}{1 - \sqrt{1 - \sin^2(B/2)}} \quad (2.18)$$

If it is assumed that  $\sin(B/2)$  is very small, then:

$$\Delta z = \frac{2\lambda}{\sin^2(B/2)} \quad (2.19)$$

however, the numerical aperture of a lens is defined as:

$$\text{N.A.} = \text{SIN } B/2 \quad (2.20)$$

and using the assumption that the angle  $B$  is very small,

$$\text{N.A.} = B/2 \quad (2.21)$$

On the other hand,  $B$  can be written as:

$$B = D/f \quad (2.22)$$

From (2.21) and (2.22),

$$\text{N.A.} = (1/2) D/f = (1/2) F \quad (2.23)$$

and thus (2.19) can be written as:

$$\Delta z = \frac{2\lambda}{(1/2F)^2} = 8\lambda F^2 \quad (2.24)$$

Equation (2.24) indicates that if the wavelength of the light and the  $F$  number used are known, the depth of focus can be calculated.

### 2.1.2 Thick lenses

A thick lens can be considered as an optical system consisting of several thin lenses, therefore one can generalize the methods mentioned for the thin lens to find the expressions needed for thick lenses.

Consider the thick lens shown in Fig. 2.7. The first and second focal points, or the so-called the object and

image foci, can conveniently be measured from the two outermost vertices ( $V_1$  and  $V_2$ ). The incident and emerged rays will meet at points, the locus of which forms a curved surface that may or may not reside within the lens. The surface, approximating a plane in the paraxial region, is termed the principal plane. Points where the primary and secondary principal planes intersect the optical axis is known as the first and second principal points,  $H_1$  and  $H_2$  respectively. They provide very useful references from which to measure several of the system parameters.

The expression for the effective focal length of a thick lens, if immersed in air, is given by:

$$1/f = 1/p + 1/q , \quad (2.25)$$

provided that both the object and image distances are measured from the first and second principal planes, respectively.

Given the location of the principal planes of a thick lens, or a set of thin lenses, the equations given for the thin lens can all be generalized. The terms used in this case will all carry the subscript "eff.", when used in the future, so that the equations for a single lens are not confused with the equations for systems of lenses. In other words any optical system can be considered as a single lens with an effective focal length, an effective F number, an

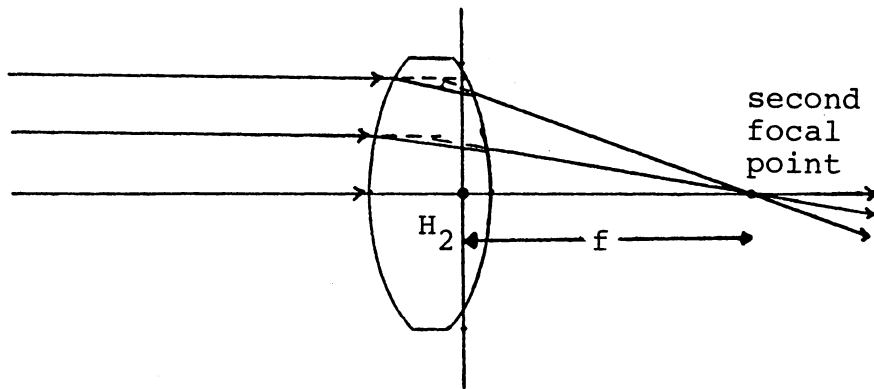
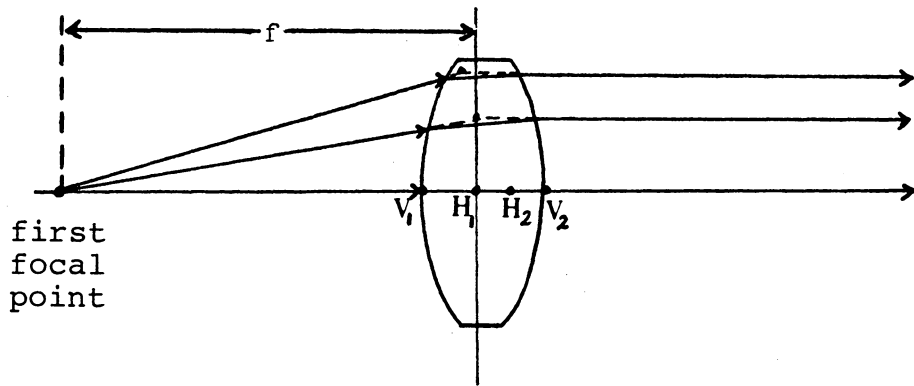


FIGURE 2.7: A thick lens.

effective depth of focus, and an effective depth of field.

## 2.2 Annular Aperture

An annular aperture can be defined as a pupil with a central obstruction. If a circular pupil function of radius "a" is considered, then the annular can be described by its radius "b" which is less than "a". In practice, however, the annular aperture is described by the ratio of its radius and the pupil's radius, denoted as "e". An annular aperture is shown in Fig. 2.8, where the shaded area shows the central obstruction.

Following the same procedure as in the case of the thin lens, the uncertainty principle can be used to find the depth of focus of a lens with the central obstruction. Consider the lens shown in Fig. 2.9, where the radius of the physical opening of the aperture stop is given by "a", and the inner radius is given by "b". The difference in momentum along the Z-axis between the ray passing the upper part of the aperture stop and the ray passing the upper part of the central obstruction is given by:

$$\Delta m = \Delta m_a - \Delta m_b , \quad (2.25)$$

where, from section 2.1.1,

$$\Delta m_a = \frac{h}{\lambda(1 - \cos B/2)} , \quad (2.26)$$

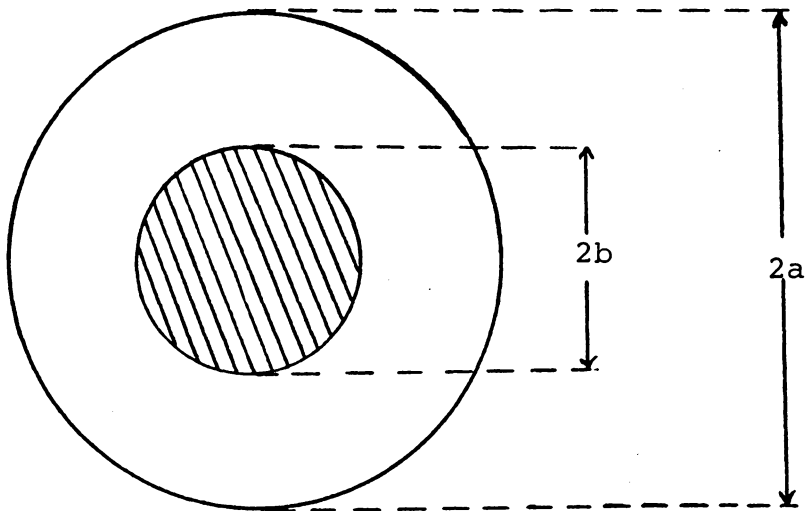


FIGURE 2.8: Annular Aperture

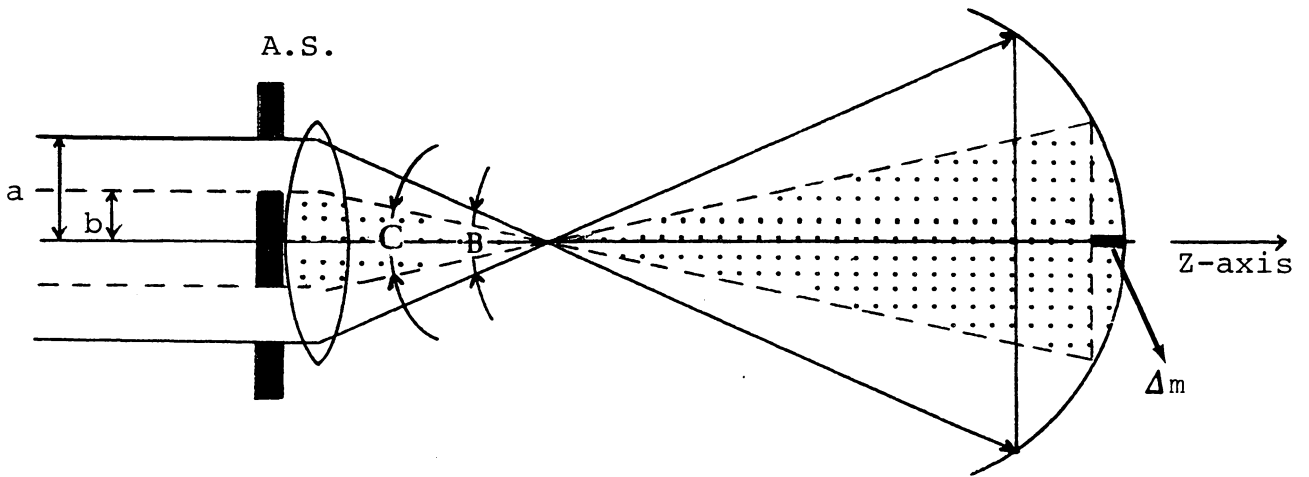


FIGURE 2.9: Uncertainty principle to find the depth of focus of system with annular aperture.

and, similarly,

$$\Delta m_b = \frac{h}{\lambda(1 - \cos C/2)} . \quad (2.27)$$

Therefore, the uncertainty in the momentum of the system is given by:

$$\Delta m = \frac{h}{\lambda[\cos C/2 - \cos B/2]} . \quad (2.28)$$

The depth of field is then given by:

$$\Delta z = \frac{\lambda}{[\cos C/2 - \cos B/2]} , \quad (2.29)$$

which can be shown to have the form:

$$\Delta z = \frac{\lambda}{\frac{1}{\sqrt{1 + e^2/4F^2}} - \frac{1}{\sqrt{1 + 1/4F^2}}} , \quad (2.30)$$

and assuming  $F^2 \gg 1/4$ , and for small values of  $s$ ,

$$\sqrt{1 + s} \approx 1 + s/2 ,$$

equation (2.30) can be approximated by:

$$\Delta z = \frac{8 \lambda F}{1 - e^2} . \quad (2.31)$$

It should be mentioned that the numerator of (2.31) is the same as the equation derived for the depth of focus of the single lens with no annular aperture. Therefore the depth of focus of a system with a central obstruction is greater than the depth of focus of the system without the obstruction by a factor of  $K$ , where  $K$  is given by:

$$K = \frac{1}{1 - e^2} . \quad (2.32)$$

Linfoot and Wolf [5] showed the same expression for the increase of the depth of focus, and in 1956, Edward L.

O'Neill [15] evaluated the transfer function of the annular aperture for different  $e$ 's. However, before considering the results of his evaluation of the transfer function, the transfer function of an optical system should be defined.

For an incoherent imaging system the image intensity distribution is given by the convolution of the object intensity distribution with the impulse response of the system. The optical transfer function, which describes the behaviour of the system, is therefore given by the ratio of the Fourier transform of the image intensity distribution and the Fourier transform of the object intensity distribution. If the OTF of the system in terms of the pupil function is desired, one can consider the optical transfer function to be the autocorrelation of the pupil function. Considering an in focus system with a square aperture as its pupil function, the OTF can be shown to have the form as in Fig. 2.10. In the same figure the transfer functions of an out of focus system and a severely out of focus system are shown. It can be noticed that the out of focus systems:

- a) Have isolated zeros; information is lost at these frequencies;
- b) Cause the OTF to have negative values in certain bands of frequency;

- c) Cause a contrast reversal when OTF is negative;
- d) Cause a rapid distortion of the response of the lens at high frequencies.

Following the definition given for the optical transfer function of the systems in incoherent light, the transfer function for the annular aperture can be found by evaluating the autocorrelation of the pupil function with the central obstruction. If the maximum radius of the pupil function is given by "a", and the inner radius by "b", as before, then the convolution can be visualized by considering Fig. 2.11. The distance, or the displacement between the center of the pupil and the center of its conjugate is denoted by "x", and it is assumed that the convolution is done from left to right, that is the pupil centered at the so called origin is stationary, and the other one is moving on it from left to right. Originally, when the two centers are overlaid, the maximum region of overlap occurs which causes the highest magnitude of the OTF at zero frequency. This magnitude is then given to be:

$$|\text{OTF}(0)| = \pi[a^2 - b^2] , \quad (2.33)$$

or, in terms of "e",

$$|\text{OTF}(0)| = \pi a^2 [1 - e^2] . \quad (2.34)$$

Similarly, the characteristics of the annular aperture at any frequency can be obtained. The desired results for the

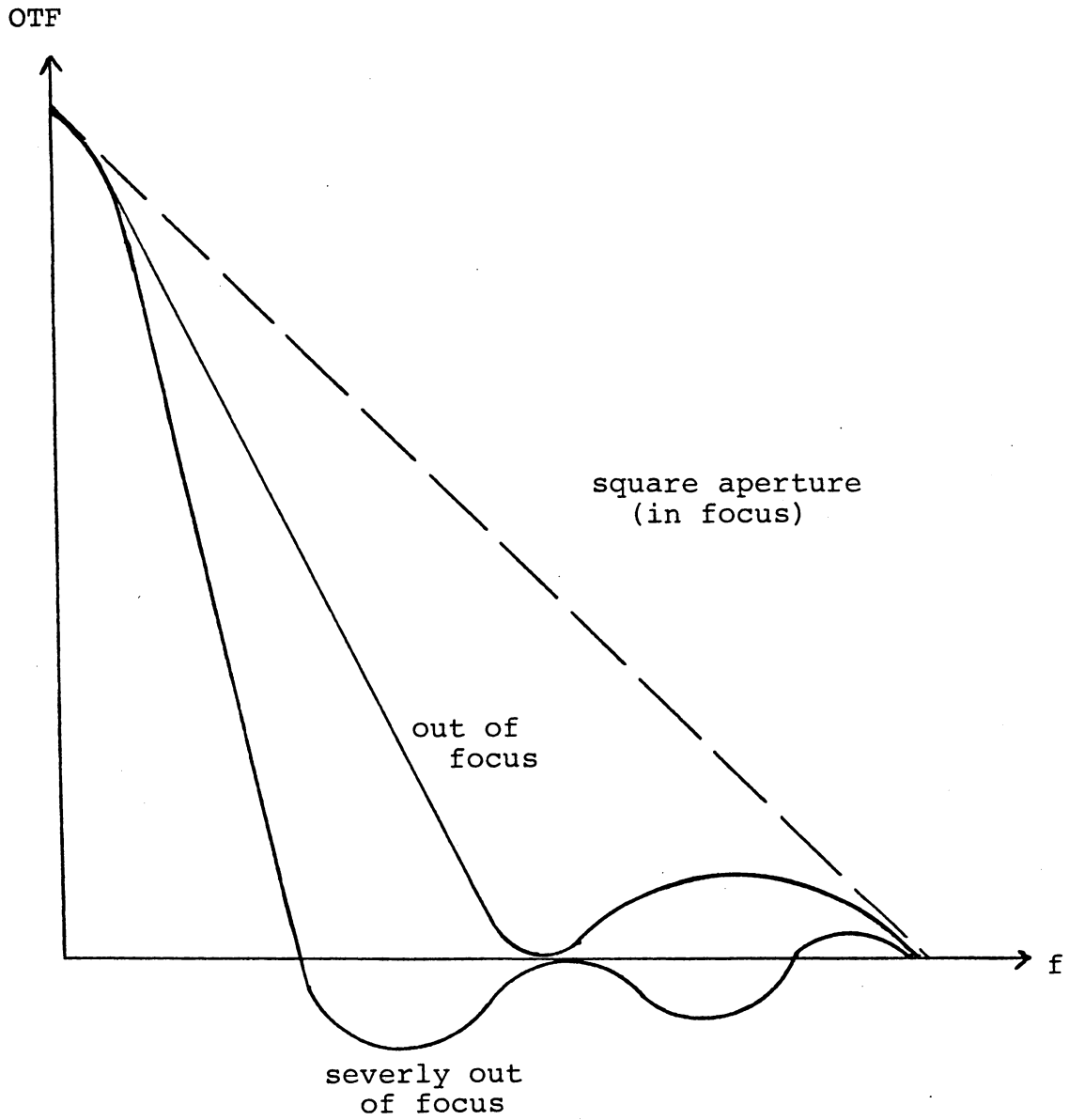


FIGURE 2.10: Optical transfer function.

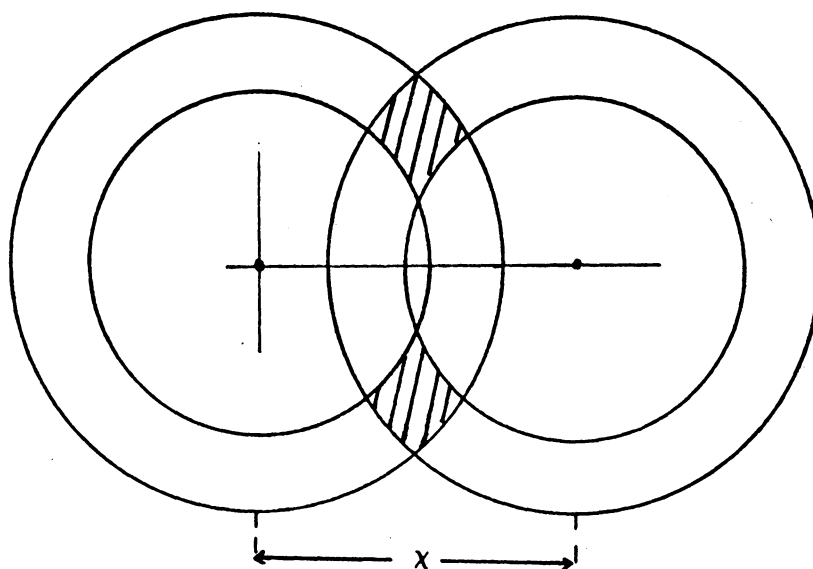
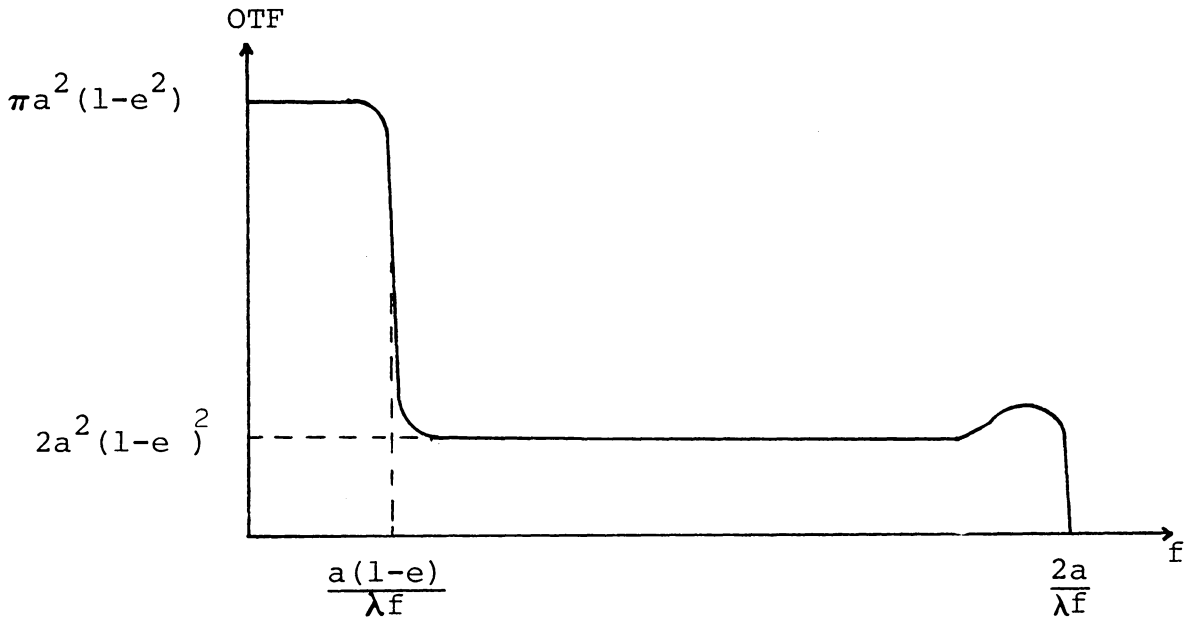


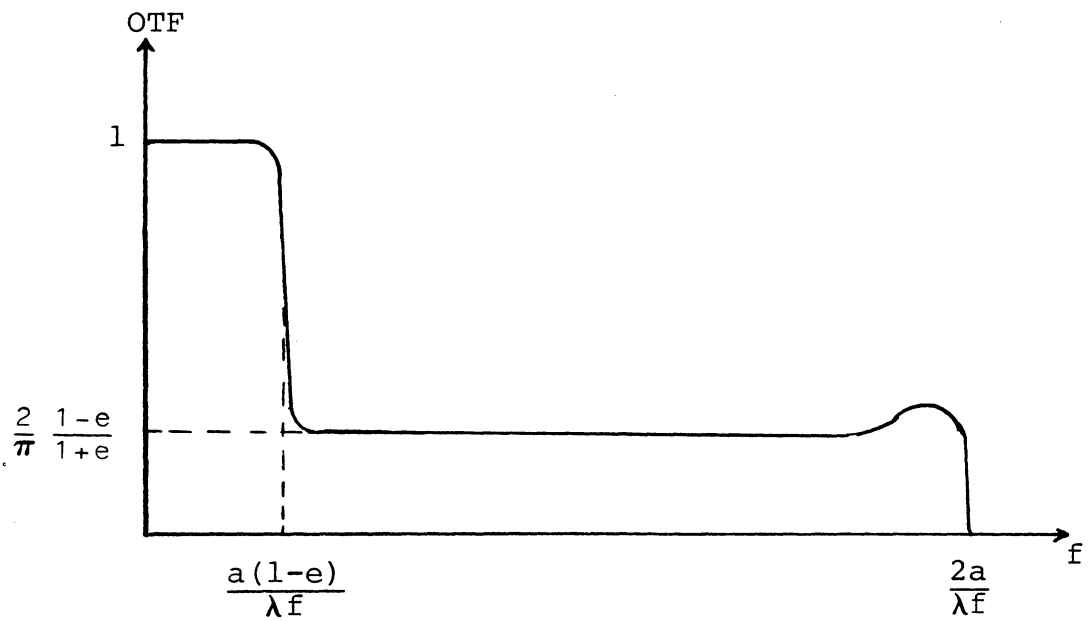
FIGURE 2.11: Auto-correlation of the annular pupil.

study of the optical system with the extended depth of focus are shown in Fig. 2.12a, and the normalized OTF is shown in Fig. 2.12b.

The evaluation of the optical transfer function of the annular aperture for different values of "e" are shown in Fig. 2.13. The results of the evaluation indicate that by the insertion of the annular aperture in front of an optical system, the low frequency response of the system will be emphasized at the expense of the high-frequency details.



(a)



(b)

FIGURE 2.12: (a) The OTF of annular aperture, (b) Normalized OTF.

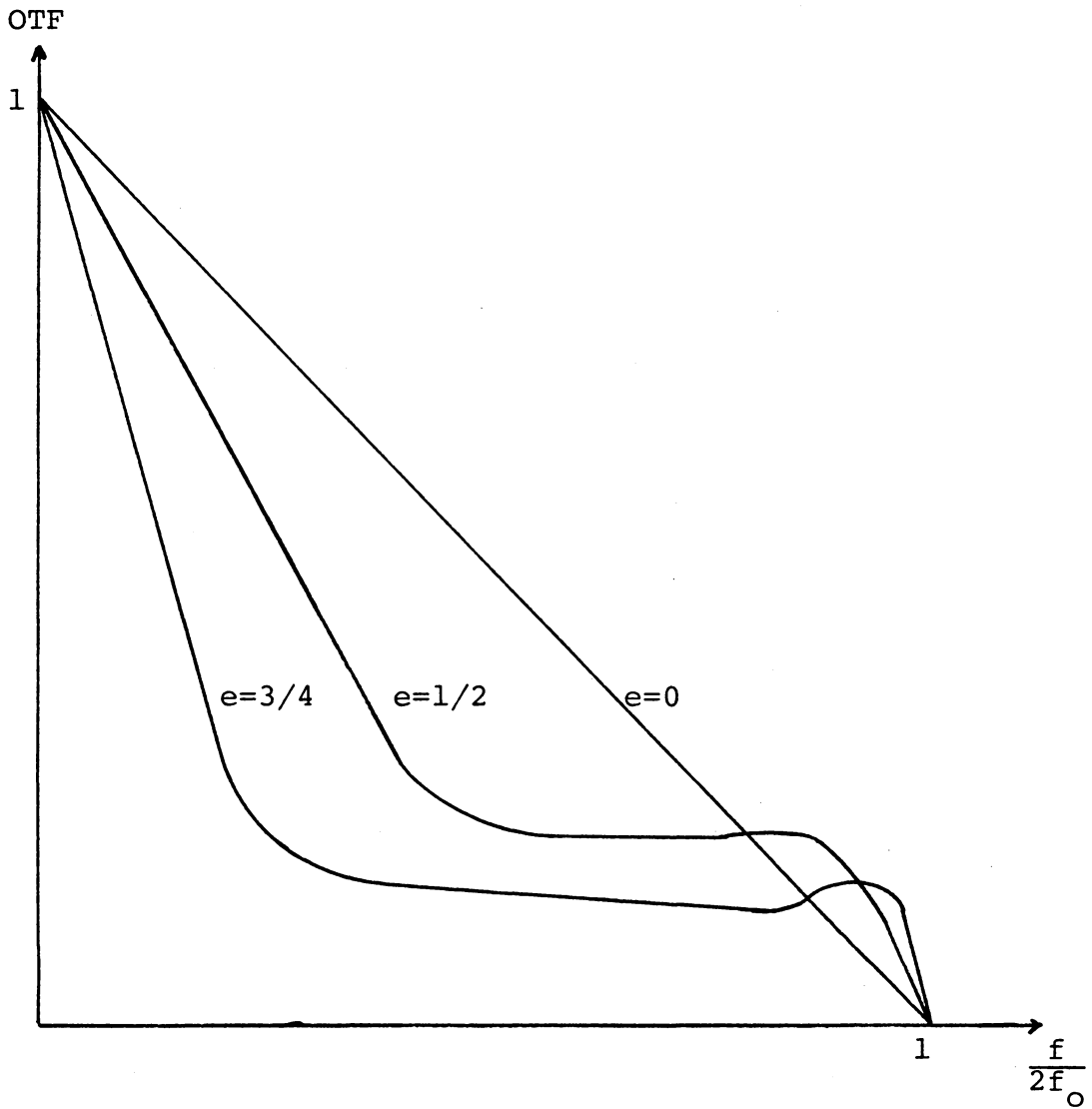


FIGURE 2.13: The OTF of annular aperture for different  $e$ 's.

### 2.3 Annular-Pass filter

In the last section it was established that by using an annular aperture in an optical system, the depth of focus can be increased. However, in the process of increasing the depth of focus, this method results in a loss of image contrast. That is, the high frequency components of the image will largely be attenuated, while passing the low frequency components (including d.c. component) essentially unattenuated. So the detailed information of the image is imbedded in a strong low-frequency background. This can clearly be seen from the OTF of the annular aperture as shown in Fig. 2.12.

Consider an image at the output of a system with an annular aperture. This degraded system has an OTF of the form described in Fig. 2.12. If one could come up with an exact inverse of this OTF, the ideal image can be restored. By considering the optical transfer function of the annular aperture, a filter of the form shown in Fig. 2.14, will compensate for the frequency or the detail losses. Notice that the Annular-Pass filter described is given in the frequency domain, as is the OTF of the annular aperture. By choosing the proper cutoff frequencies the image can be restored to have a constant OTF.

In using the annular-pass filter it should be realized

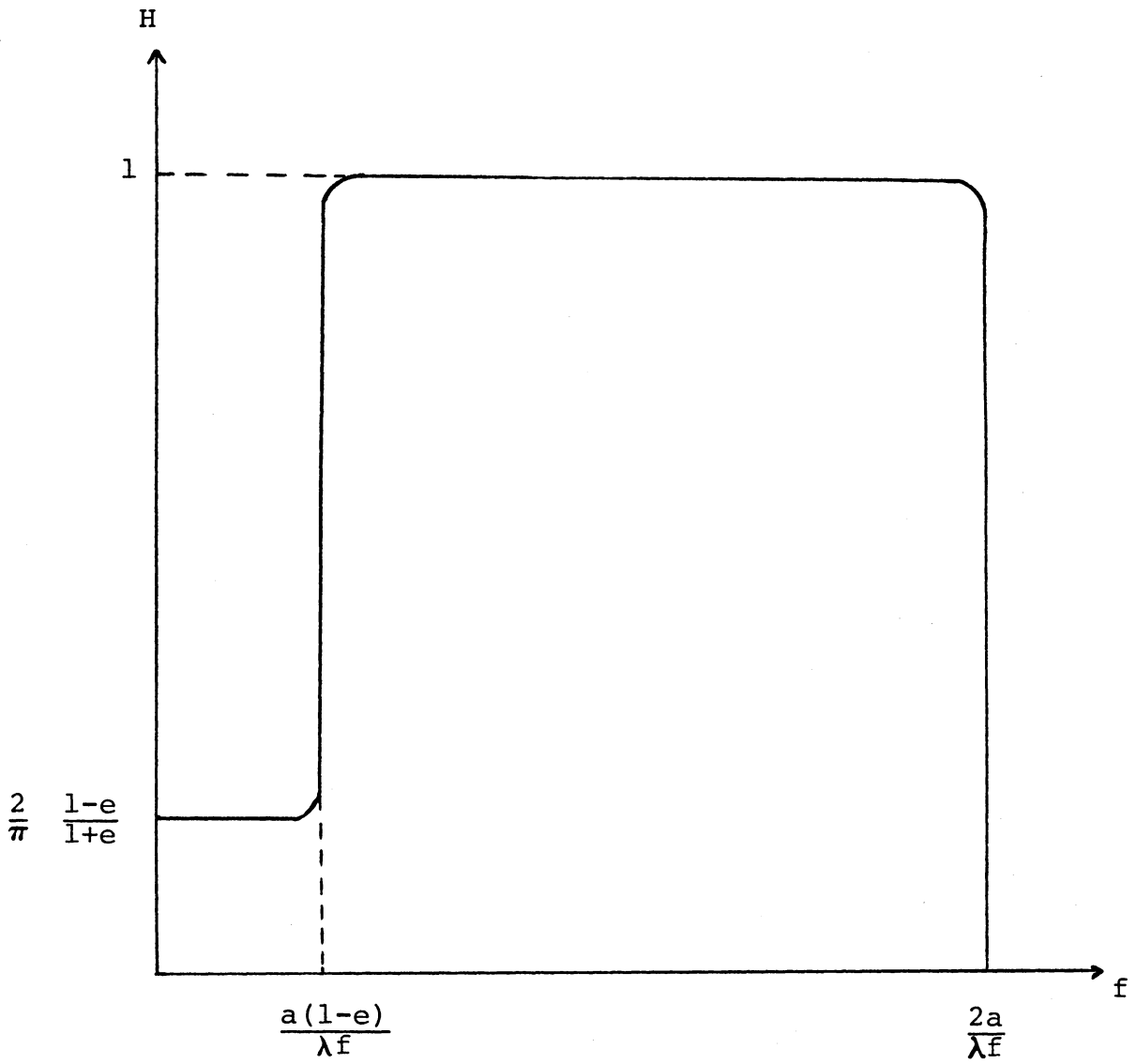
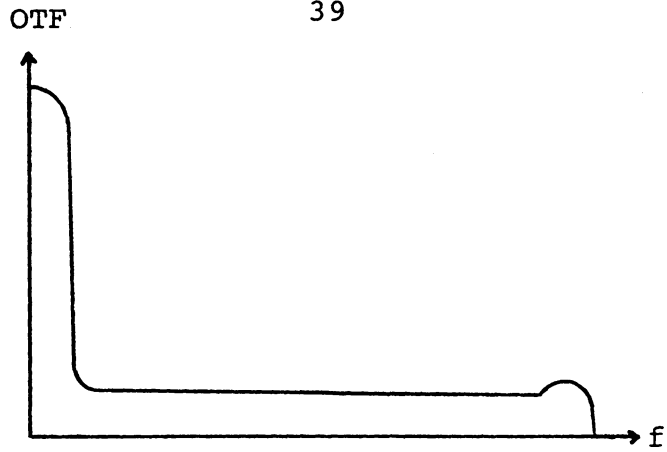
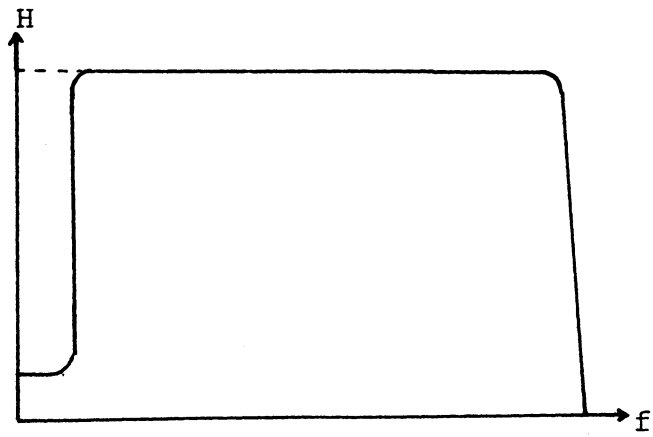


FIGURE 2.14: The annular-pass filter.

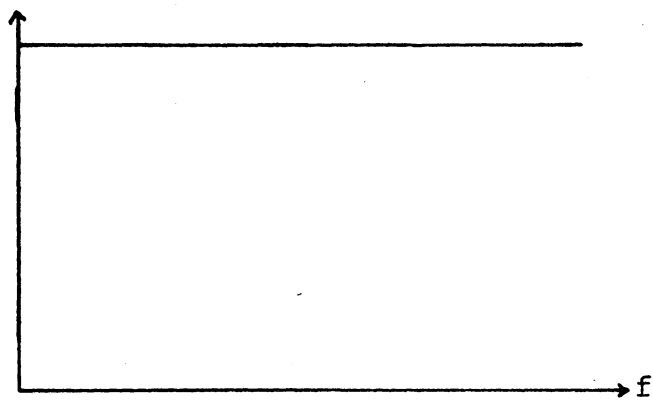
that the filtering will not be exact unless the precise OTF of the system is measured. However, if the transfer function of the degraded system, when an annular aperture used, is known, the result described in Fig. 2.15 is obtainable.



(a)



(b)



(c)

FIGURE 2.15: The effect of ideal annular-pass filter.

## Chapter III

### DISCRETE TIME FILTERING

From the two-dimensional linear system theory[16], it is evident that there are two mathematical techniques available for implementation of spatial filtering principles- convolution and Fourier transformation. In a computer environment, convolution is equivalent to vector circulant matrix multiplication which is normally used when not all degrees of freedom in the definition of filter function are required. On the other hand, to fully utilize the power of computer approach, all degrees of freedom will become necessary, especially in matched filtering, and therefore Fourier approach will be pursued.

#### 3.1 The Discrete Fourier Transform

Since the operation performed by a lens can be described by a Fourier transform equation, it is possible to simulate optical processing on digital computer by evaluating the two-dimensional Fourier transform of a function mathematically. If  $f(x,y)$  is a two dimensional array of points of dimension  $N$  by  $N$ , the two-dimensional Fourier transform,  $F(u,v)$ , in discrete form, is defined as:

$$F(u, v) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x, y) \text{Exp} \left[ -\frac{2i}{N} (xu + yv) \right] . \quad (3.1)$$

Equation (3.1) describes the relationship between the spatial domain and spatial frequency domain representation of discrete signals, thereby the name discrete Fourier transform (DFT) is used.

There are a number of fast DFT computational techniques known collectively as the fast Fourier transform (FFT) algorithm. To understand the fast Fourier transform algorithm, the two dimensional function can be considered as  $N$  one-dimensional functions, thus the algorithm can be defined for one-dimensional functions and then generalized. Consider a DFT  $F(u)$  of dimension  $N$ , with

$$F(u) = \sum_{x=0}^{N-1} f(x) W^{ux} , \quad (3.2)$$

$$u = 0, \dots, N-1$$

where,

$$W = \text{Exp} \left[ -\frac{2i}{N} \right] . \quad (3.3)$$

If  $N$  is the product of two factors, with  $N = N_1 N_2$ , we can redefine the indices  $u$  and  $x$  by [16]:

$$x = N_1 x_2 + x_1, \quad x_1, u_1 = 0, \dots, N_1 - 1 \quad (3.4)$$

$$u = N_2 u_1 + u_2, \quad x_2, u_2 = 0, \dots, N_2 - 1 \quad (3.5)$$

Substituting (3.4) and (3.5) into (3.2) yields:

$$F(N_2 u_1 + u_2) = \sum_{x_1=0}^{N_1-1} W^{N_1 x_1 u_1} W^{x_1 u_2} \sum_{x_2=0}^{N_2-1} f(N_1 x_2 + x_1) W^{N_1 x_2 u_2} \quad (3.6)$$

or, with  $W^{N_2} = \text{Exp} \left[ -i2\pi/N_1 \right] = W_1$  and  $W^{N_1} = \text{Exp} \left[ -i2\pi/N_2 \right] = W_2$ ,

$$F(N_2 u_1 + u_2) = \sum_{x_1=0}^{N_1-1} W^{N_2 x_1 u_1} W^{x_1 u_2} \sum_{x_2=0}^{N_2-1} f(N_1 x_2 + x_1) W^{N_1 x_2 u_2} \quad (3.7)$$

which shows that the DFT of length  $N$  can be viewed as a DFT of size  $N_1 N_2$ , except for the introduction of the factor  $W$  to power  $x_1 u_2$  called the twiddle factors[16]. Thus, the computation of  $F(u)$  by (3.2) is done in three steps, with the first step corresponding to the evaluation of the DFTs of the form  $Y_{x_1, u_2}$  corresponding to the  $N_1$  distinct values of

$$Y_{x_1, u_2} = \sum_{x_2=0}^{N_2-1} f(N_1 x_2 + x_1) W_2^{x_2 u_2}, \quad (3.8)$$

is then multiplied by the twiddle factor and  $F(u)$  is obtained by calculating  $N_2$  DFTs of  $N_1$  points on the  $N_2$  sequences  $Y_{x_1, u_2} W^{x_1 u_2}$ , with:

$$F(N_2 u_1 + u_2) = \sum_{x_1=0}^{N_1-1} Y_{x_1, u_2} W^{x_1 u_2} W_1^{x_1 u_2}. \quad (3.9)$$

The FFT algorithm derives its efficiency by replacing the computation of one large DFT with that of several

smaller DFTs. Since the number of operations required to directly compute an  $N$ -point DFT is proportional to  $N^2$ , the number of operations decreases rapidly when the computation structure is partitioned into that of many small DFTs.

One FFT method that is normally used with sequences of length  $N=2^t$ , where  $t$  is a positive integer, is the Radix-2 FFT. In this case, the first stage of the FFT can be defined by choosing  $N_1=2$  and  $N_2=2^{t-1}$ . This is equivalent to splitting the input sequence  $f(x)$  into two  $(N/2)$ -point sequences  $f(2x)$  and  $f(2x+1)$  corresponding, respectively, to the even and odd samples of  $f(x)$ . Under these conditions,  $F(u)$  becomes:

$$F(u) = \sum_{x=0}^{N/2-1} f(2x) W^{2xu} - W^u \sum_{x=0}^{N/2-1} f(2x+1) W^{2xu}, \quad (3.10)$$

and, since  $W^{N/2} = -1$ ,

$$F(u+N/2) = \sum_{x=0}^{N/2-1} f(2x) W^{2xu} + W^u \sum_{x=0}^{N/2-1} f(2x+1) W^{2xu} \\ u = 0, \dots, N/2-1 \quad (3.11)$$

The same procedure can be applied again to replace the two DFTs of length  $N/2$  by 4 DFTs of length  $N/4$ . A systematic application of this method computes the DFT of length  $2^t$  in  $t = \log_2 N$  stages, each stage converting  $2^i$  DFTs of length

$2^{t-i}$  into  $2^{i+1}$  DFTs of length  $2^{t-i-1}$ .

The Radix-2 FFT approach is illustrated in Fig. 3.1 for an 8-point DFT. In this signal flow graph, each node represents a variable and each arrow terminating at a node represents the additive contribution of the variable at the originating node of the arrow. Multiplication by a constant are represented by the constant written near the arrowhead. It should be mentioned that this method requires  $M$  complex multiplications and  $A$  complex additions, where  $M$  and  $A$  are given by[17]:

$$M = (N/2) \log_2 N , \quad (3.12)$$

$$A = N \log_2 N . \quad (3.13)$$

This approach was implemented for the use in the study of the annular aperture. The Fortran program RX2FFT, shown in Appendix A, is the implementation of the Radix-2 FFT method. Figure 3.2 displays a test scene for verification of this method. The original image, a square pattern, appears in Fig. 3.2a. The magnitude of the Fourier transform appears in Fig. 3.2b. From Fig. 3.2b it is evident that the majority of the spectral energy is concentrated along the horizontal and vertical axes.

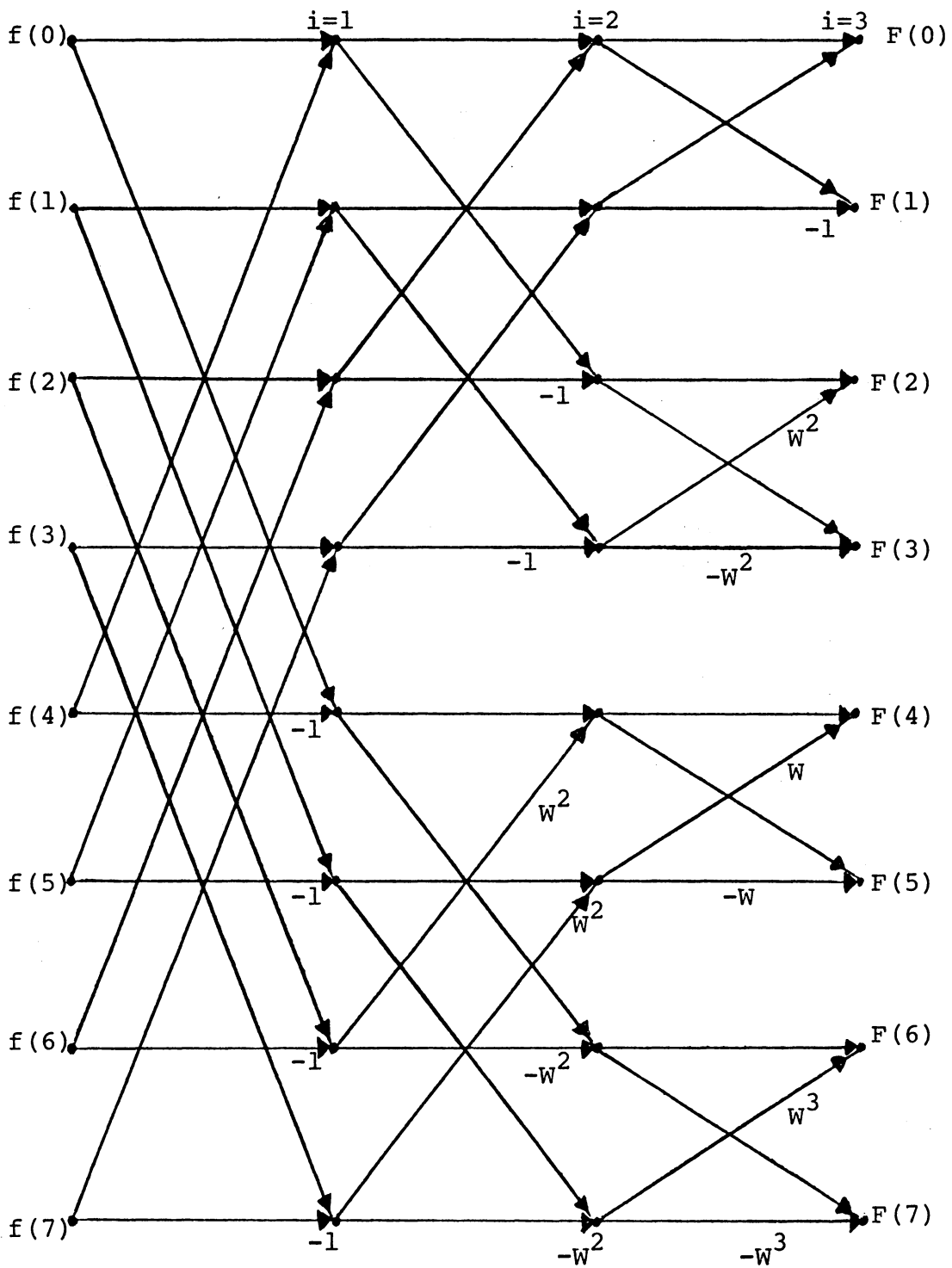
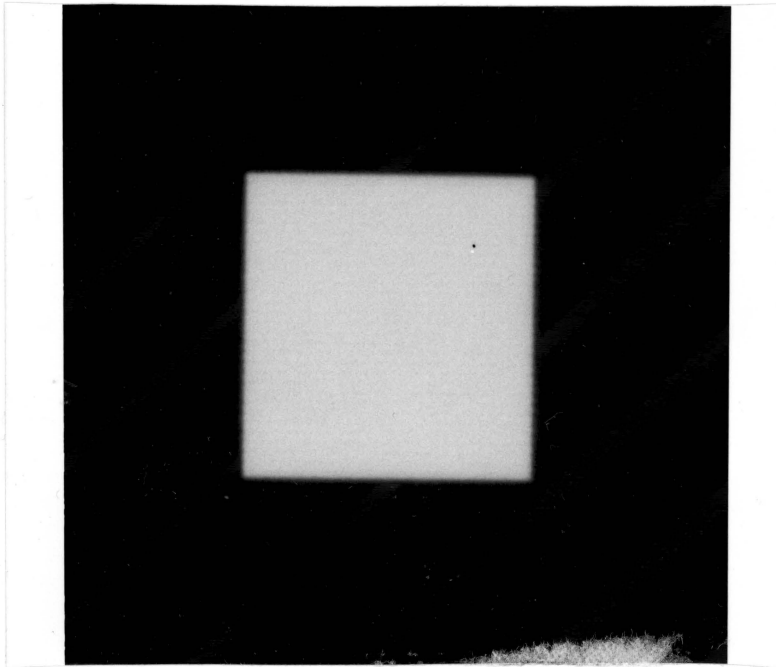
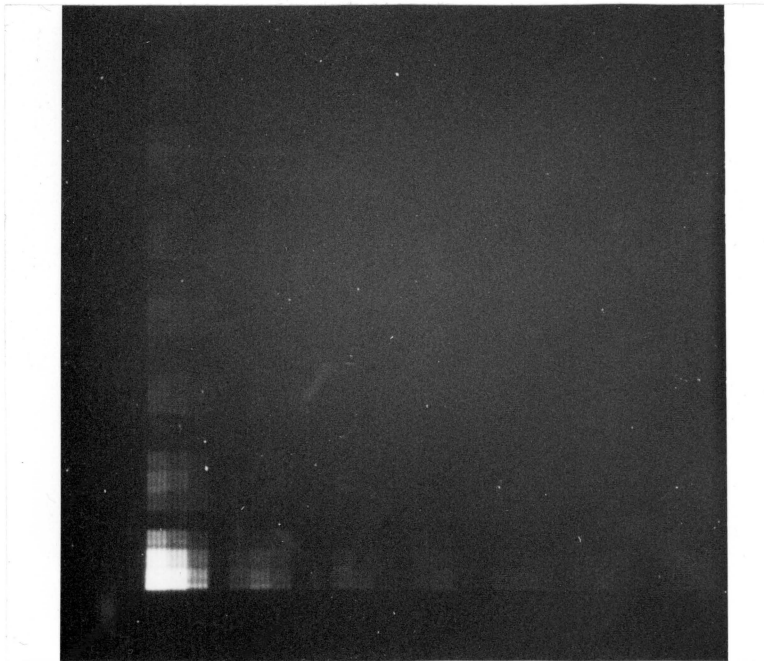


FIGURE 3.1: Radix-2 FFT signal flow graph,  $N=8$ .



(a)



(b)

FIGURE 3.2: Fourier transform: (a) Test pattern,  
(b) Magnitude of the FFT: One quadrant.

### 3.2 Two Dimensional Filtering

The goal in spatial filtering is to determine which pictorial characteristics are wanted, and separate the desired data from the incoming data. This should result in enhancement of the data, since the more the unwanted "noise" is reduced, the more visible or enhanced must be the remaining signal. Of particular interest is the capability of spatial frequency filtering to perform such functions.

The computer can filter an image by first transforming the image (by taking its FFT) into the frequency domain, where frequency selection is made. The Fourier transform approach limits filtering to global operations, that is the whole image is affected equally.

There are different two-dimensional filtering methods used in the frequency domain. Even though the "ideal" filters are non-realizable, an approximation can always be made. For example, the two-dimensional transfer function for an ideal circular low-pass filter,  $H(u,v)$ , is given by:

$$H(u,v) = \begin{cases} 1 & \text{for } \sqrt{u^2 + v^2} \leq R \\ 0 & \text{otherwise} \end{cases} \quad (3.14)$$

over one period.  $R$  is the radius of the circle in the frequency domain. The corresponding unit sample response is given by:

$$h(x,y) = \frac{RJ_1(R\sqrt{x^2+y^2})}{2\pi\sqrt{x^2+y^2}}, \quad (3.15)$$

where  $J_1$  is the Bessel function of the first kind, order one. Similarly, the frequency response of an ideal circular band-filter is given by:

$$H(u,v) = \begin{cases} 1 & \text{for } R_1 \leq u^2 + v^2 \leq R_2 \\ 0 & \text{otherwise} \end{cases} \quad (3.16)$$

and the unit sample response is:

$$h(x,y) = \frac{R_2 J_1(R_2 \sqrt{x^2+y^2})}{2\pi\sqrt{x^2+y^2}} - \frac{R_1 J_1(R_1 \sqrt{x^2+y^2})}{2\pi\sqrt{x^2+y^2}} \quad (3.17)$$

An ideal circular high-pass filter has a frequency response given by:

$$H(u,v) = \begin{cases} 0 & \text{for } u^2 + v^2 \leq R^2 \\ 1 & \text{otherwise} \end{cases} \quad (3.18)$$

and its unit sample response is given by:

$$h(x,y) = \begin{cases} 1 & \text{for } x=0 \text{ and } y=0 \\ -\frac{RJ_1(R\sqrt{x^2+y^2})}{2\pi\sqrt{x^2+y^2}} & \text{otherwise} \end{cases} \quad (3.19)$$

In all of these cases the unit sample response is of infinite extent, that is, there is no finite area outside of which the unit sample response is zero. Consequently, these filters are not realizable[18].

In implementing the compensation filter needed for the effect of the annular aperture, it is not necessary to find

the best filter possible. A discrete two-dimensional filter which passes the desired frequencies and blocks the unwanted ones can be implemented by multiplying the terms of the FFT of the original image by a factor that varies from zero to one to get no transmission to full transmission of the component. This method works. However, some error of ringing and leakage may be observed. The two-dimensional filter can be tested by observing the results of low pass and high pass filtering done on the square block of Fig. 3.2a. Figure 3.3 is the result of two-dimensional low pass filtering, which indicates that most of the information, except for the edges, is conserved. Figure 3.4, on the other hand, is the result of the high pass filtering on the same image which preserves the edge information.

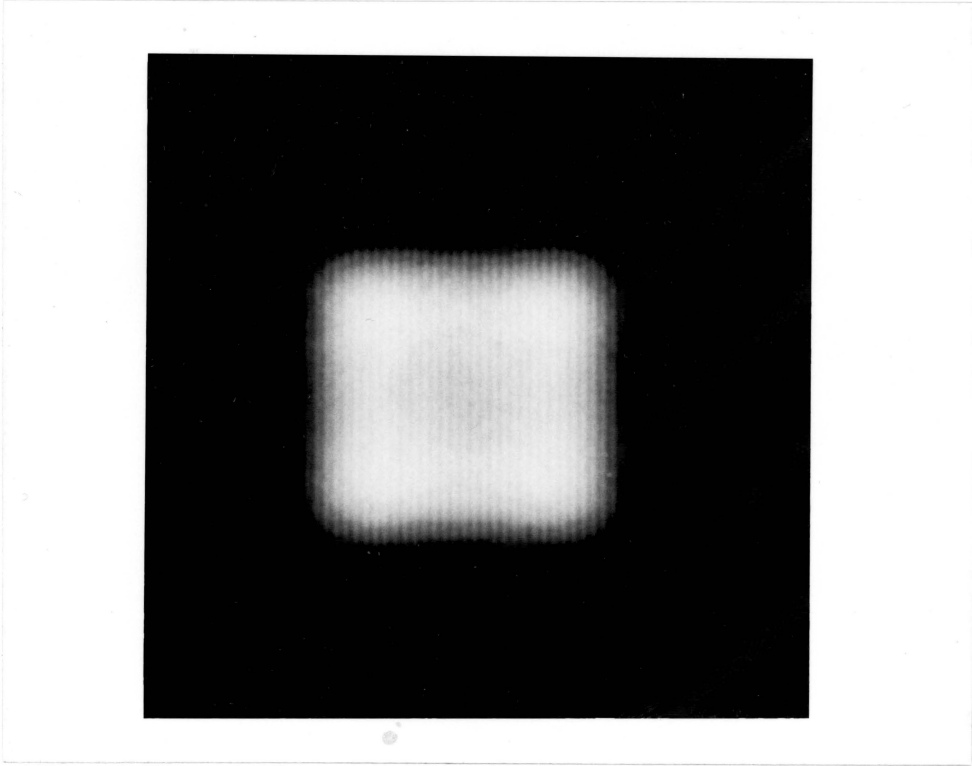


FIGURE 3.3: The Effect of Low Pass Filter

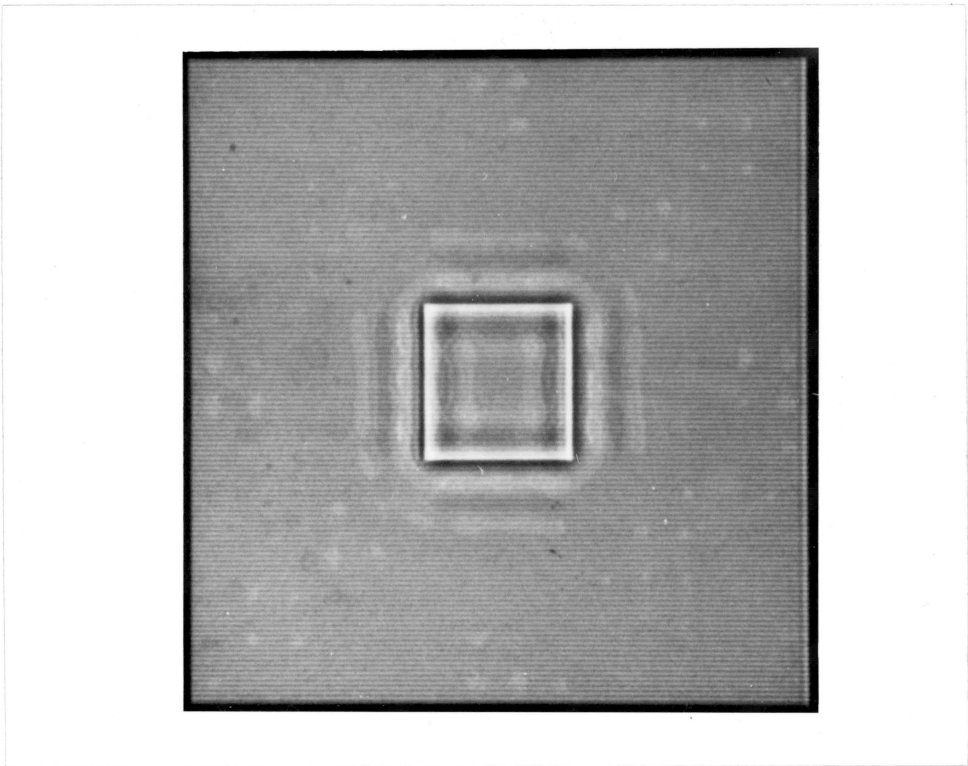


FIGURE 3.4: The Effect of High Pass Filter

## Chapter IV

### OPTICAL/DIGITAL SYSTEM

In the past, optical image processing has been performed primarily with coherent light. The use of incoherent light alleviates some of the transducer problems normally encountered when coupling optical systems with electronic systems[3]. This coupling, or hybrid processing, may include digital electronics such as TV components. The use of incoherent light compared to coherent light has the advantage of less noise level and better stability[3].

The block diagram of Fig 4.1 shows a hybrid optical/digital image processing system which consists of an optical system, a digital system, and an optical/digital system interfacing them. The three systems are discussed separately and then the overall system is considered.

#### 4.1 The Optical System

The optical system in general can consist of a set of lenses separated by different distances to obtain the proper characteristics needed in different applications. The system used in image processing is usually a regular camera lens with a constant focal length, however, there are limitations on the type of lens used. These limitations

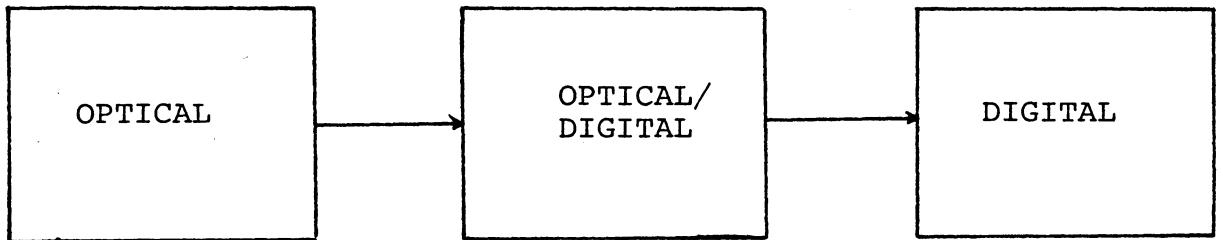


FIGURE 4.1: Block diagram of an Optical/Digital system.

varies from one application to the other.

If a photographic lens is to be designed and constructed for some particular application, it is essential that some important factors are decided on. Some of the factors to be considered are as follows[9]:

(a) The distance of the object (or image) : The desired focal length, angular field, and relative aperture (F-Number) should be specified.

(b) Finite magnification: If the lens is to be used at finite magnification, the sizes of the image and object, the distance from object to image, and the effective F-number must be specified.

(c) Wavelength region: The range of the wavelengths under control must be known.

(d) Field Coverage: It is necessary to specify if the field is to be flat or curved.

The optical system needed to study the effects of the annular aperture may:

- (a) Have a constant focal length,
- (b) Operate in a wide range,
- (c) Have a wide angular field,
- (d) Cover flat fields, and
- (e) Operate in normal light wavelength.

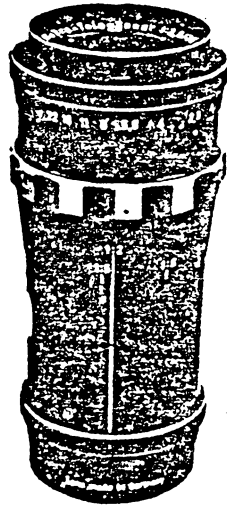
These specifications are met by a lens of the form

shown on Fig. 4.2. The lens consists of a set of thick lenses, separated by constant distances, and a movable hollow cylinder. The lens combination can be thought of as one lens with an effective focal length of "f" as shown on Fig. 4.3.

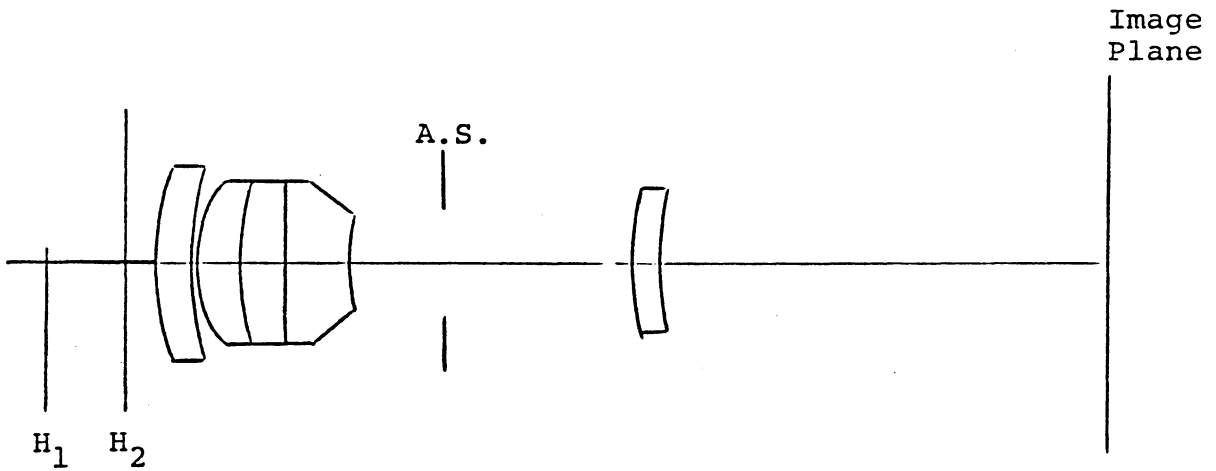
The lens shown in Fig. 4.2 is the Makro-Tele-Xenar lens which is manufactured by the Schneider company of Germany. The lens is an 8 mm movie lens with a focal length of 75mm. It can operate at a distance of 30cm away from the lens up to infinity, however, at distances below one meter the effective magnification varies from 1:2 to 1:10, and the system has a one to one magnification at distances above a meter away from the lens. The effective F-number ranges from 2.8, which is the maximum opening, to 22 which is the minimum. The manufacturer specifies the ratio of the entrance angle to the exit angle to be 0.60[19]. The two principal planes, as described in chapter 2, are shown in both figures 4.2 and 4.3. It should be mentioned that the annular should ideally be put on the first principal plane.

#### 4.2 The Digital System

The digital system consists of computer hardware, software, and devices needed to display the image and its



(a)



(b)

FIGURE 4.2: The Makro-Tele-Xenar lens.

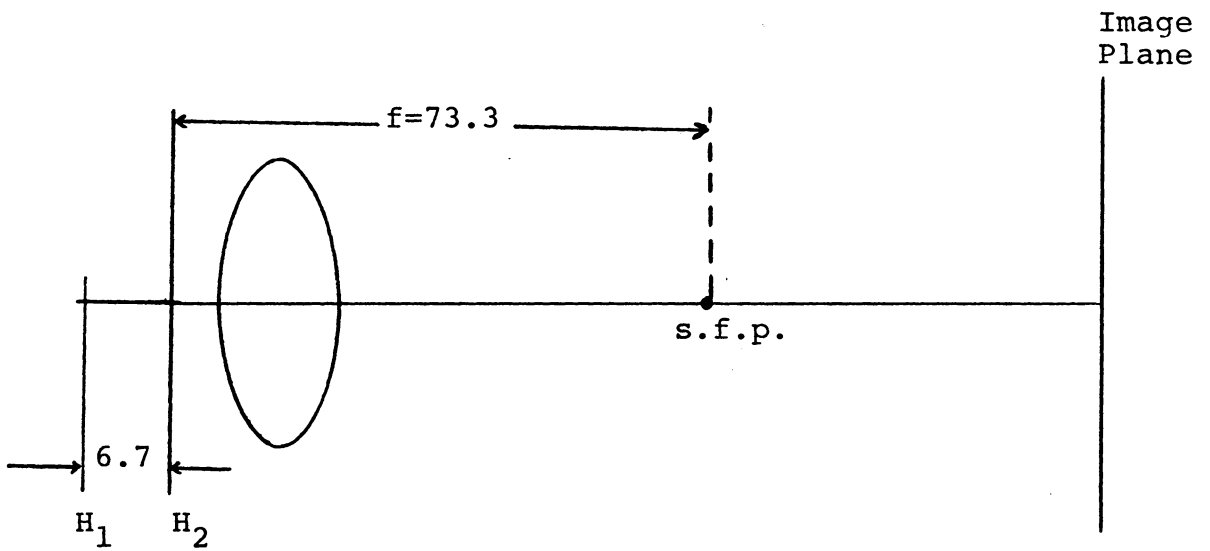


FIGURE 4.3: The effective lens,  
(Units in mm).

transform. The interface, as will be discussed in the next section, is an optical to digital converter which is connected to the memory of the computer where the digitized image will be saved for future use.

Figure 4.4 shows the complete block diagram of the digital system where the computer includes all of the software and hardware needed for image processing. The processes involved in a particular application are inputted and monitored, from the keyboard, by the user. The results are saved on magnetic tapes and can be displayed on the TV monitor.

The software used depends on the particular application, however, if one is interested in the frequency domain filtering of a given image, a fast Fourier transform routine can be used to get the discrete Fourier equivalent of the image and then the result can be filtered by a two-dimensional user-generated filter whose cutoff frequencies can be inputted. The inverse fast fourier transform can be applied to attain the desired filtered image.

The system used for this research consists of a VAX 11 computer which is capable of running image processing software. The digitizer is the system developed by the Vicom company; the display is a Matrix display connected to the Polaroid camera.

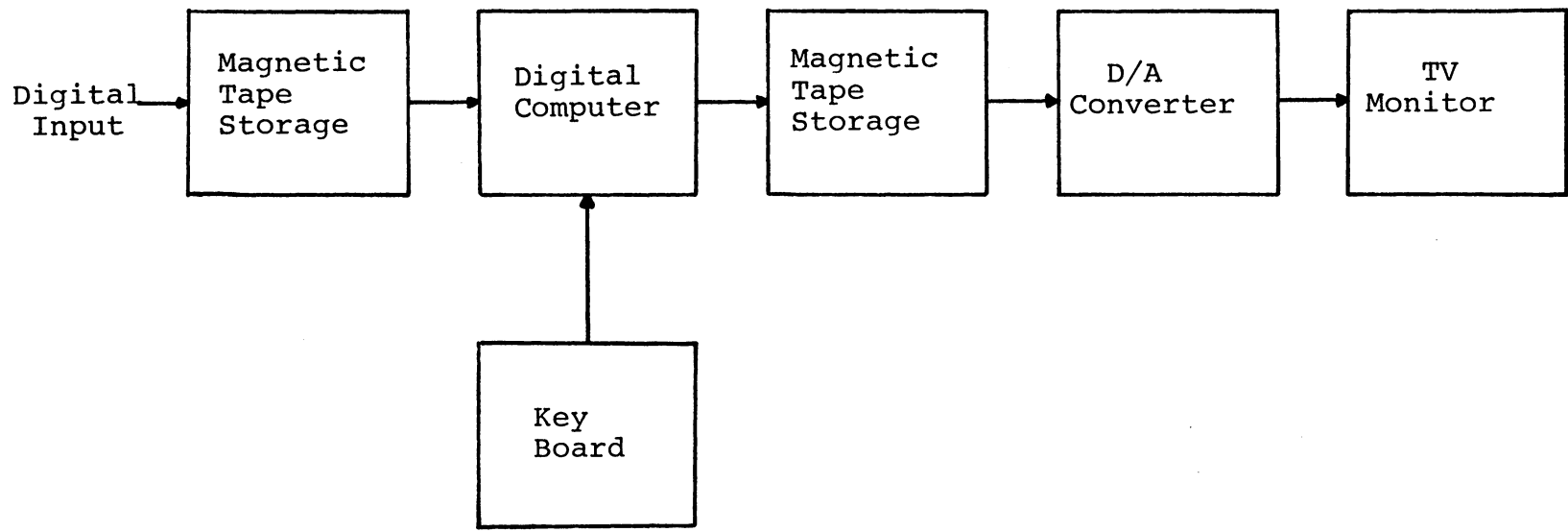


FIGURE 4.4: The block diagram of a digital system.

### 4.3 The Optical/Digital Interface

The system needed to interface the two systems should be capable of accepting optical signals and converting them to discrete data. A typical image scanning system capable of giving the desired results is shown on Fig. 4.5. In operation a narrow light beam is discretely scanned across a positive transparency of an ideal image. The light passing through the transparency is collected by a condensor lens and directed toward the surface of a photoconductor. The electrical output of the photoconductor is integrated over the time period during which the light beam strikes a resolution cell. The value of each resolution cell is then converted to a binary code and thus the digital output is obtained[20].

In using incoherent light extremely small points of light are raster scanned onto a CRT with intensity of each point set proportional to the image sample magnitude. The light array on the CRT can then be imaged onto the computer memory using special circuitry[20].

### 4.4 The complete system

The combination of the optical system, the digital system, and their interface, as applied to image processing with an extended depth of field, is shown on Fig. 4.6. The

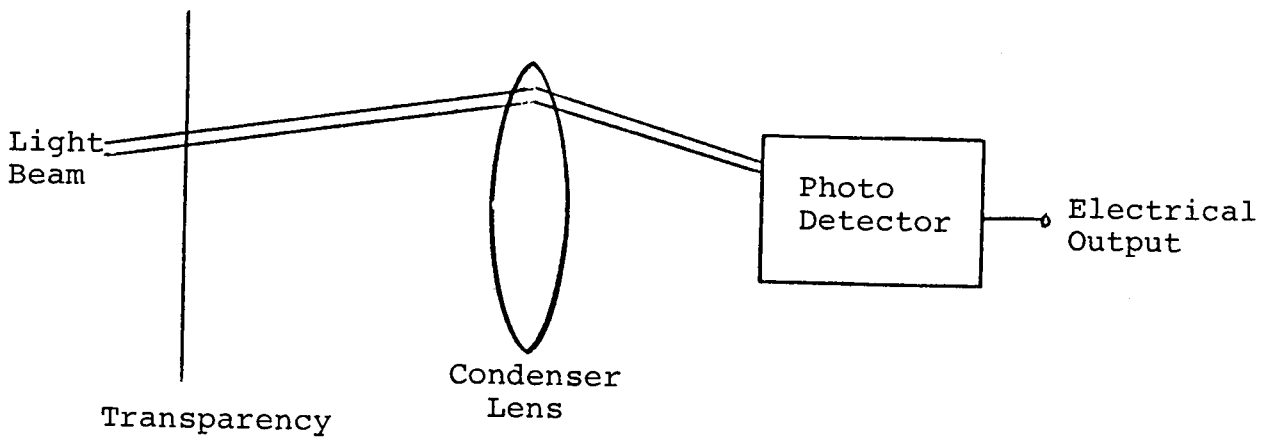


FIGURE 4.5: Typical image scanning system.

optical section is the Macro-Tele-Xenar lens which is connected to a vidicon camera. The camera is then connected to a CRT through some electronics circuitry by which the digitization is then performed. This digitized image, as was mentioned before, is saved on magnetic tapes for future use. The output, after the desired operations are performed, can be displayed on the TV monitor. Pictures of the output, or the image, displayed on the TV monitor can be taken using Matrix camera units.

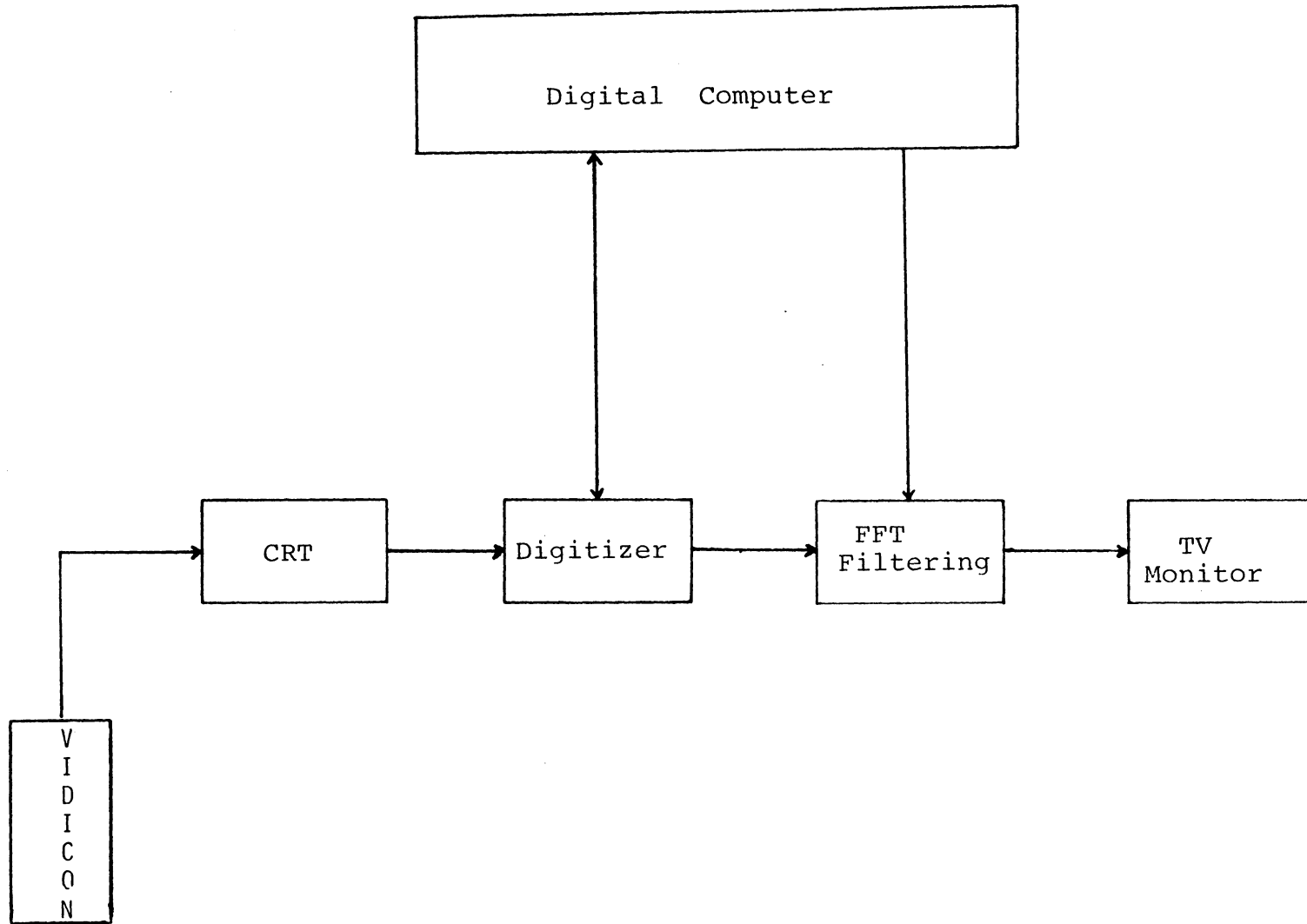


FIGURE 4.6: The incoherent image processing system.

## Chapter V

### EXPERIMENT AND RESULTS

The study of the effects of the annular aperture on the depth of focus of an out of focus system involves two different, but related procedures. The first procedure, or step, can be described as a purely optical procedure, whereby a focused system is brought out of focus by moving the object, or the lens, closer or further away from the in focus position. Then by insertion of an annular aperture in front of the lens the system is brought back into focus. The second procedure involves the calculation of the Fourier transform of the obtained image and the filtering of the transform; therefore it can be called a purely digital procedure.

#### 5.1 Optical Procedure

The first step in the optical procedure is to find out if the annular aperture will indeed increase the depth of field of the system. A test pattern can be chosen to analyze the effects of the annular. If the system is in focus, as shown in Fig. 5.1, then the effect of the annular aperture can be described as a high frequency attenuator. This effect can be noticed in Fig. 5.2, where an annular of

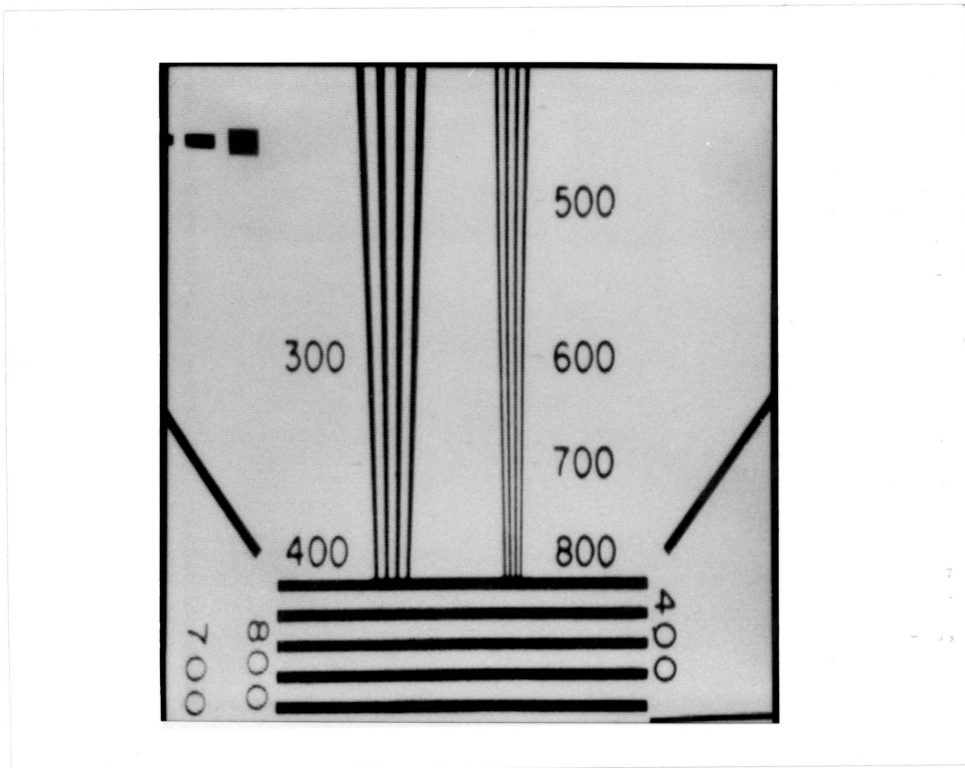


FIGURE 5.1: In focus test pattern (no annular)

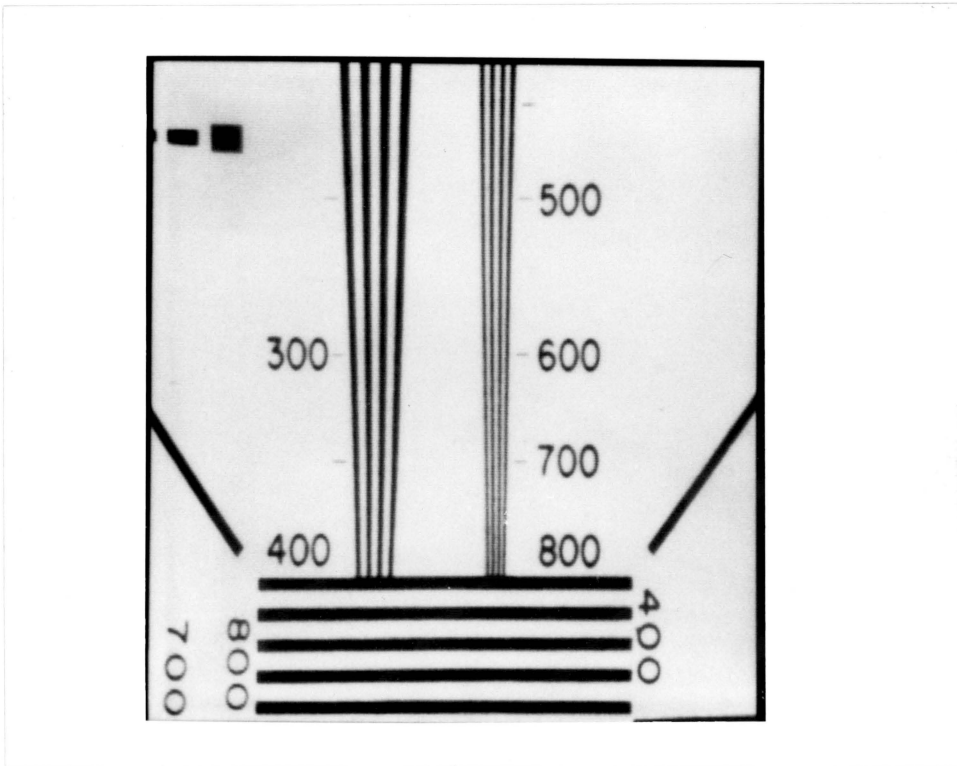


FIGURE 5.2: In focus test pattern (annular:  $e=0.51$ )

0.51 is used. The obtained image is still in focus, as expected, however, the lines observed are thicker than before, and also the image has lost some of its contrast. The same effects can also be noticed in Fig. 5.3, where the effect of the loss in contrast is more obvious since a larger annular is used ( $e=0.64$ ). The loss of contrast can clearly be viewed in Fig. 5.4, where an annular of  $e=0.80$  is used. It can be noticed that the shadow of the annular on the image is starting to be present (See Appendix B). The use of annular apertures in front of an in focus system, not only does not improve the actual characteristic of the system, but it also causes a loss of contrast.

In order to bring the system out of focus, the camera can be moved closer or further away from the object. The settings on the camera, such as the F-number and the distance control should be kept constant at the same positions as in the focus case. The test pattern shown in Fig. 5.5 shows the same pattern as in Fig. 5.1 with no annular, however the camera has moved a distance of 33 millimeters away from the original plane. It can be noticed from this figure that the numbers on the figure can not really be distinguished, thus the system is indeed out of focus. Now if there is an annular that can be inserted in front of the lens, then the system can be brought back into

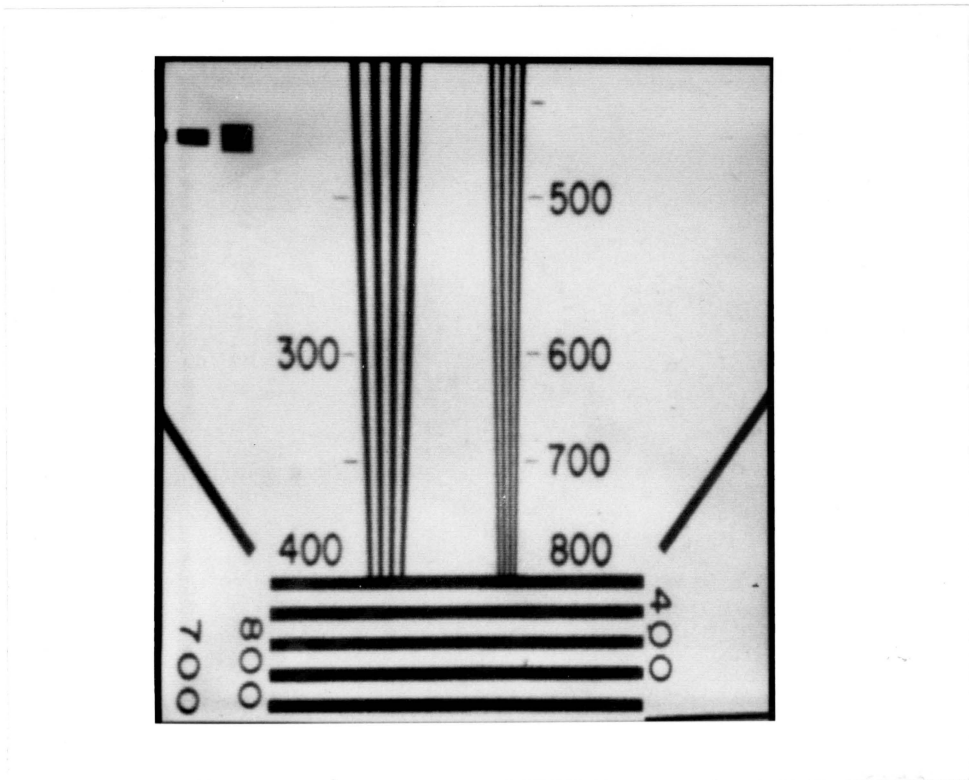


FIGURE 5.3: In focus test pattern (Annualer:  $e=0.64$ )

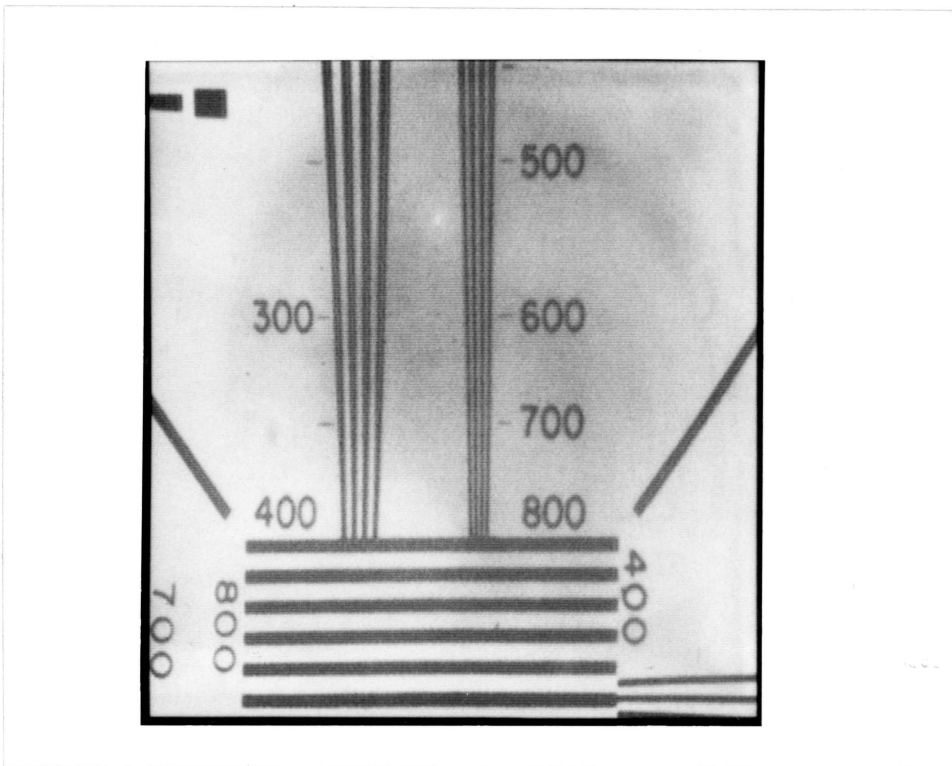


FIGURE 5.4: In focus test pattern (Annular:  $e=0.80$ )

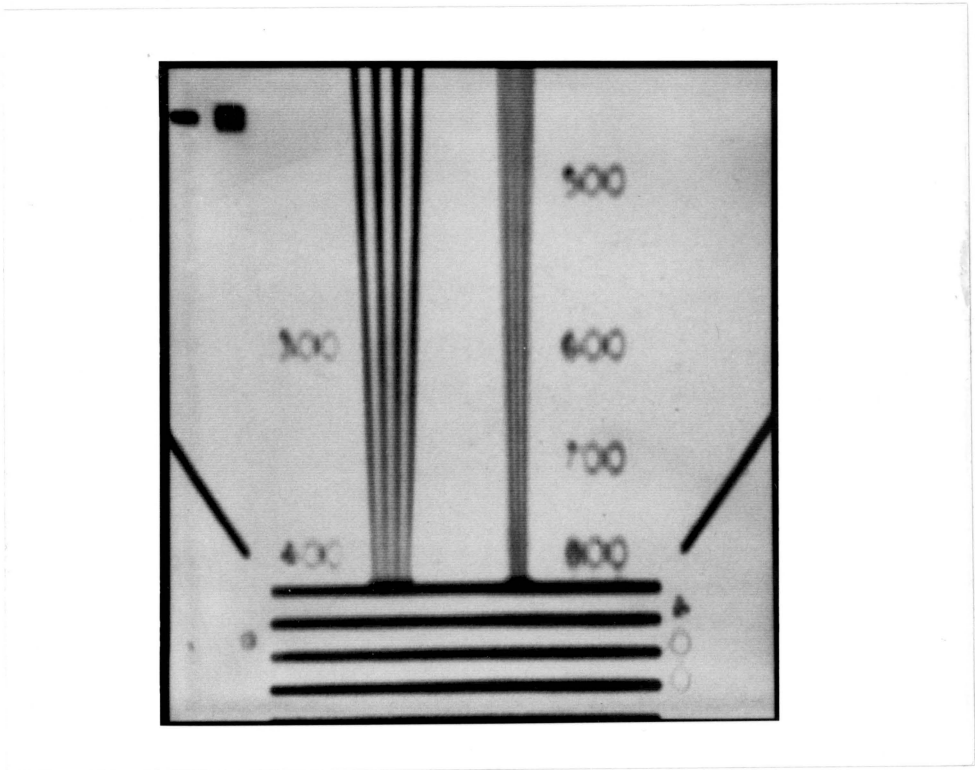


FIGURE 5.5: Out of focus test pattern (No annular)

focus with some loss of contrast. The idea is to increase the depth of field to an extent that the writing is recognizable. If the same annulus of the case of in focus image are used, the results shown in figures 5.6, 5.7, and 5.8 are obtained, which correspond to  $e=0.51$ ,  $e=0.64$ , and  $e=0.80$ , respectively.

Consider Fig. 5.6, where an annular of  $e=0.51$  is used. A close comparison of images 5.5 and 5.6 indicates that the "zeros" are more distinguishable, and most of the other numbers can be recognized. It also indicates that the annular aperture will preserve the shape of the image.

It can be noticed that as the size of the aperture is increased, more details of the out of focus image are observable. This is specially apparent in Fig. 5.8, where, even though a shadow is present, the numbers are mostly recognizable.

This will lead to the conclusion that an annular aperture will indeed increase the depth of field of a system. Therefore an exact knowledge of the amount of defocusing can lead to using the proper annular to bring the system into focus. The amount of defocusing should be given in terms of the depth of field of the system, if known, and the size of the annular can be then calculated using (2.32).

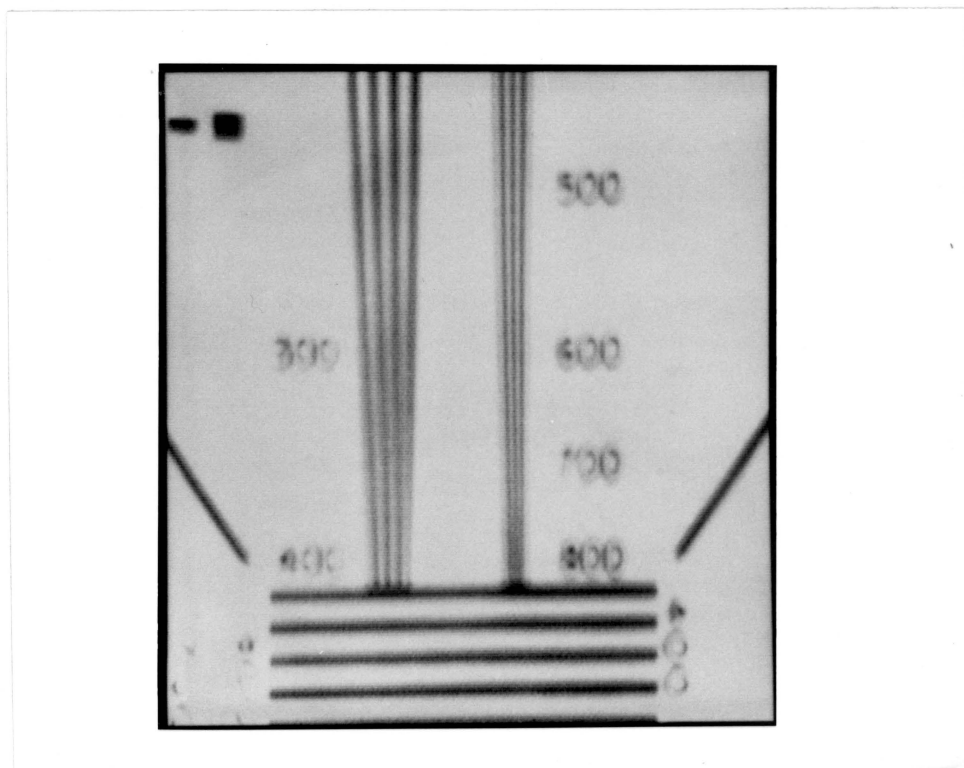


FIGURE 5.6: Out of focus test pattern (Annular:  $e=0.51$ )

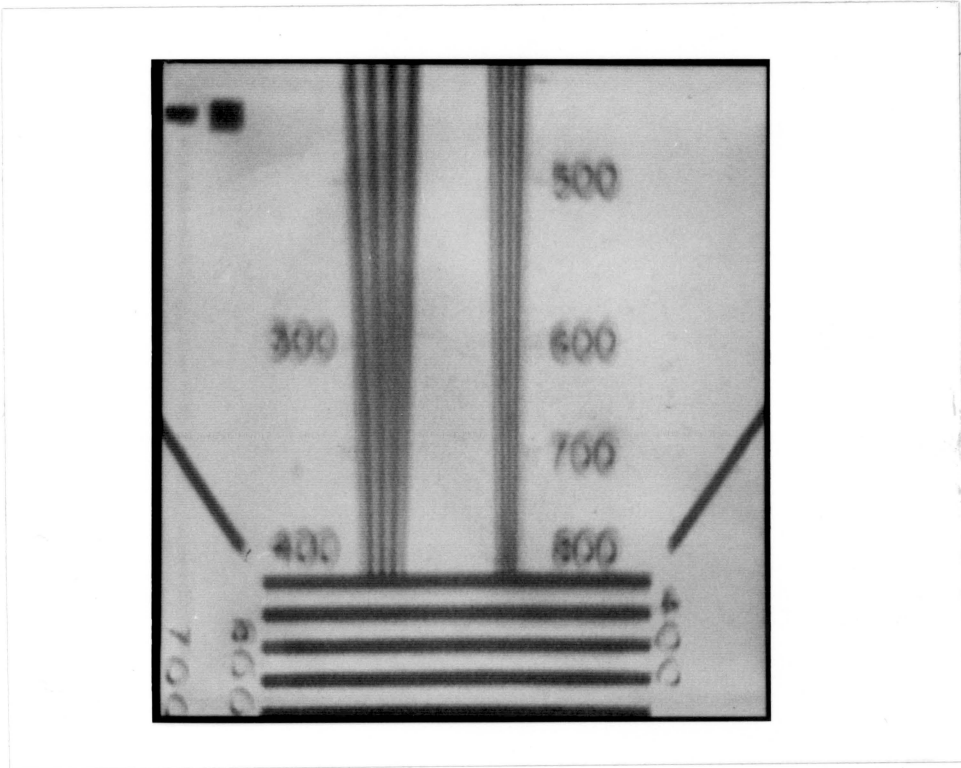


FIGURE 5.7: Out of focus test pattern (Annular:  $e=0.64$ )

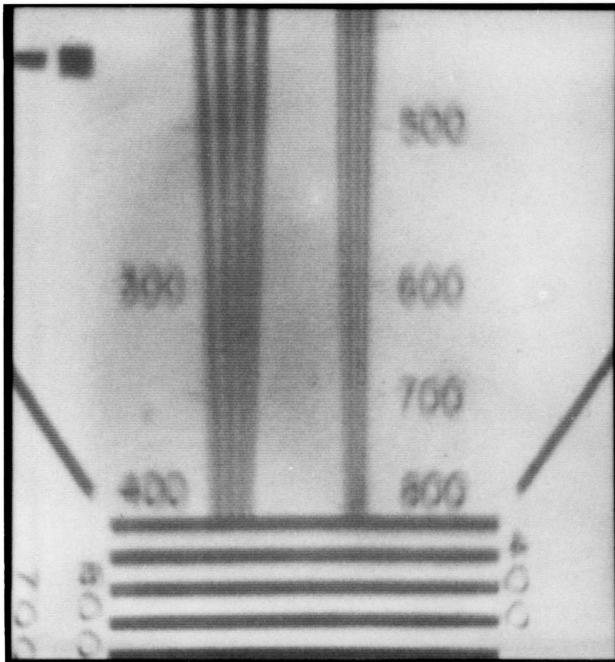


FIGURE 5.8: Out of focus test pattern (Annular:  $e=0.80$ )

## 5.2 Digital Procedure

The digital processing of the image begins after insertion of the annular aperture. The process involves taking the FFT of the image and then applying the annular pass filtering on it. The filtered results are then taken through an inverse FFT and the output is the corrected image.

It should be mentioned that the filtering done on the image is not an ideal filtering; it is only a filter to compensate quantitatively some of the loss of contrast due to the annular aperture, and no attempt is made to reconstruct an ideal image. This point can be observed by filtering a portion of the image shown in Fig. 5.2. Since an annular of  $e=0.51$  is used, it can be seen that the lines are thicker than the in focus case. Consider the portion of Fig. 5.1 shown in Fig. 5.9, and compare it with Fig. 5.10 which is the same portion but from Fig. 5.2. It is evident that the lines are thicker when the annular is used. The annular-pass filtering of Fig. 5.10 is shown in Fig. 5.11, and as can be seen in that figure the lines are back to their original size, however, there is a discoloring of the background as well as some artifact, which is due to the non-ideal characteristics of the filter used.

Having the knowledge that the filtering is non-ideal,

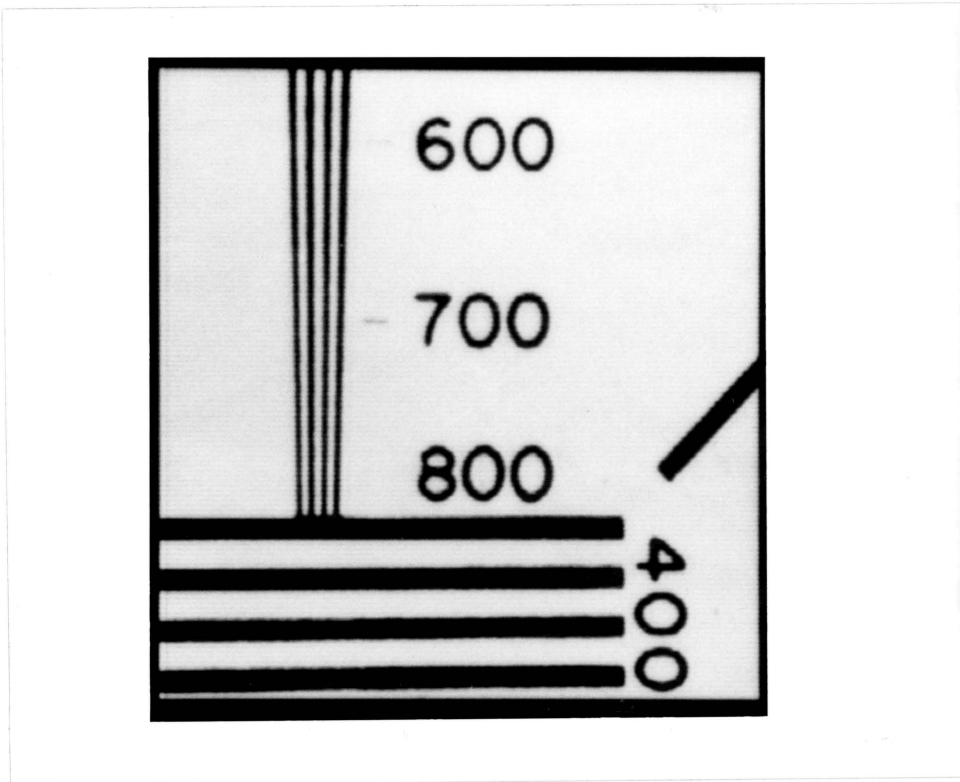


FIGURE 5.9: A section of an in focus image.

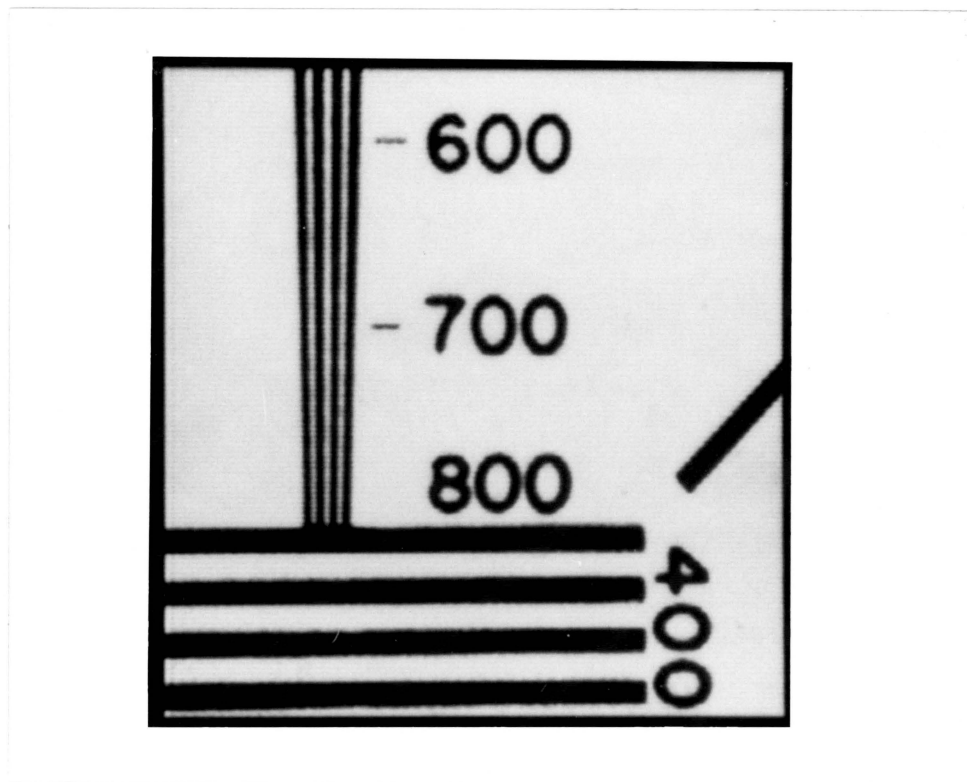


FIGURE 5.10: Out of focus version of 5.9 (Annular: 0.51)

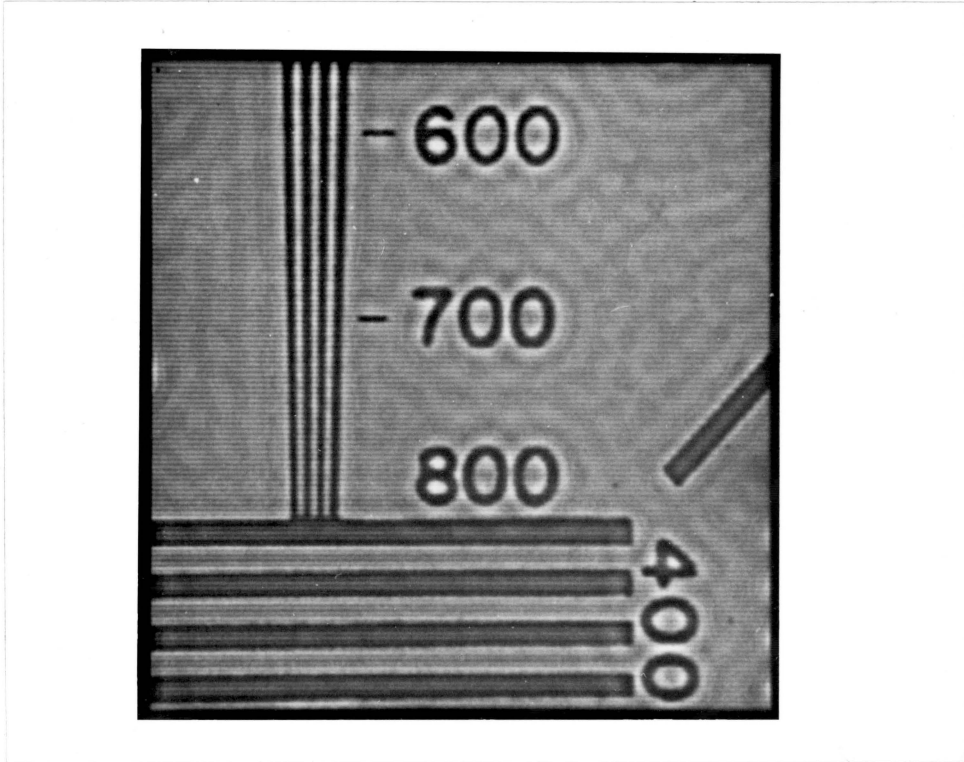


FIGURE 5.11: Filtered version of figure 5.10.

we can strive for the detection of the shapes present on the image so that the image can be recognized.

The filter was shown to produce non-ideal results when used in an in-focus environment, however, if a spoke pattern of the form shown in Fig. 5.12(a) is taken out of focus so that a ring is observed, as seen from Fig. 5.12(b), an annular of the size  $e=0.53$  can be used to bring the spoke back into focus. The results indicate that the ring is indeed gone, however, the width of the lobes of the spoke, after the annular, are thicker than the original in-focus image as can be seen in Fig. 5.12(c). The filtering will then restore the lobes a little closer to their original size. This pattern was used in calibrating the filtering.

The effects of the system were then studied by using written text. The image "VIRGINIA TECH", as shown in Fig. 5.13, was first taken out of focus by a distance equal to 20 millimeters. The out of focus text, as shown in Fig. 5.14, was then processed using an annular aperture of the size  $e=0.20$ , which resulted to the image shown in Fig. 5.15. This resulting image is in focus and the filtering done on it will make the edges much clearer. The filtered image is shown in Fig. 5.16.

The text was then taken out of focus by 26 millimeters. This corresponded to a severe out of focus in which none of

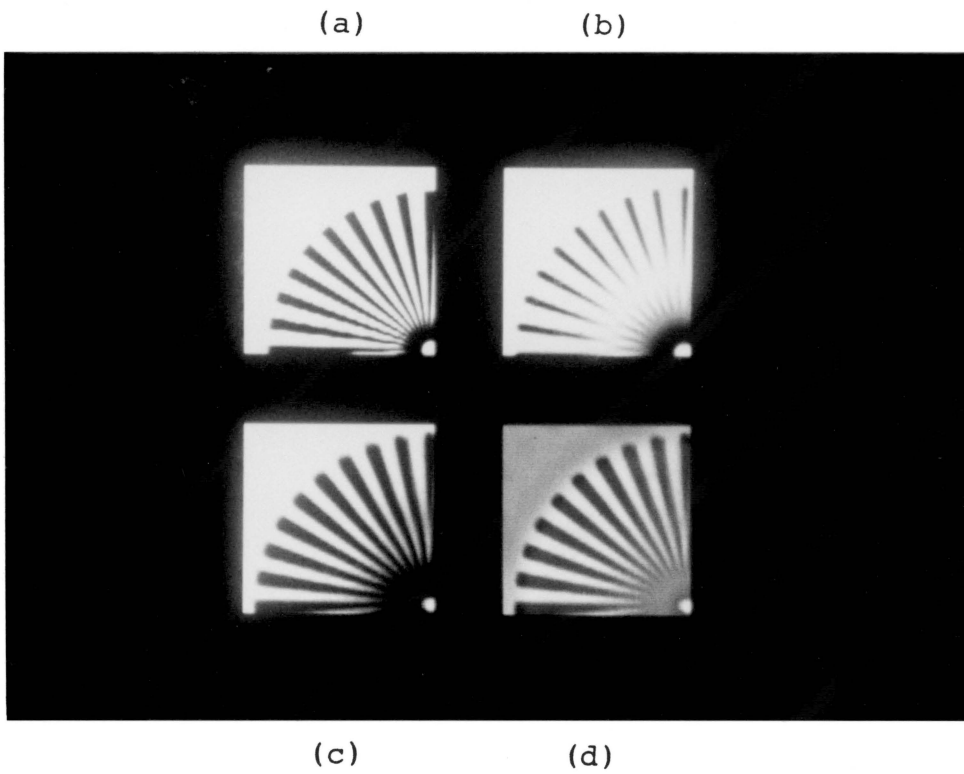


FIGURE 5.12: (a) In focus spoke, (b) Out of focus spoke,  
(c) Annular:  $e=0.53$ , (d) Filtered results.

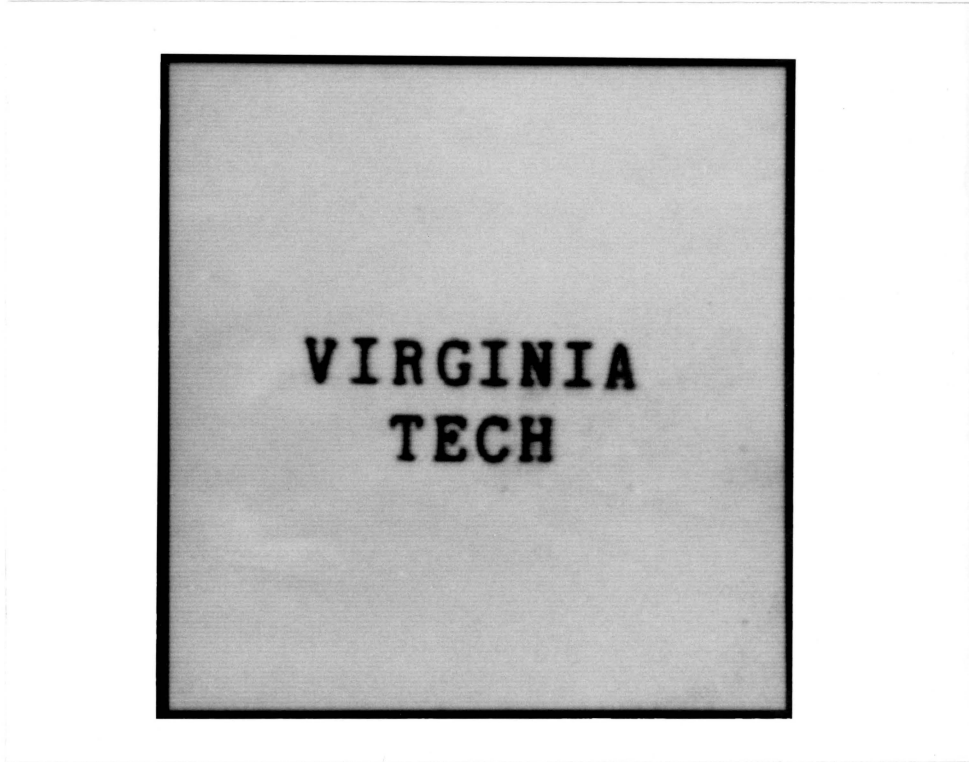


FIGURE 5.13: In focus text.



FIGURE 5.14: Out of focus text.

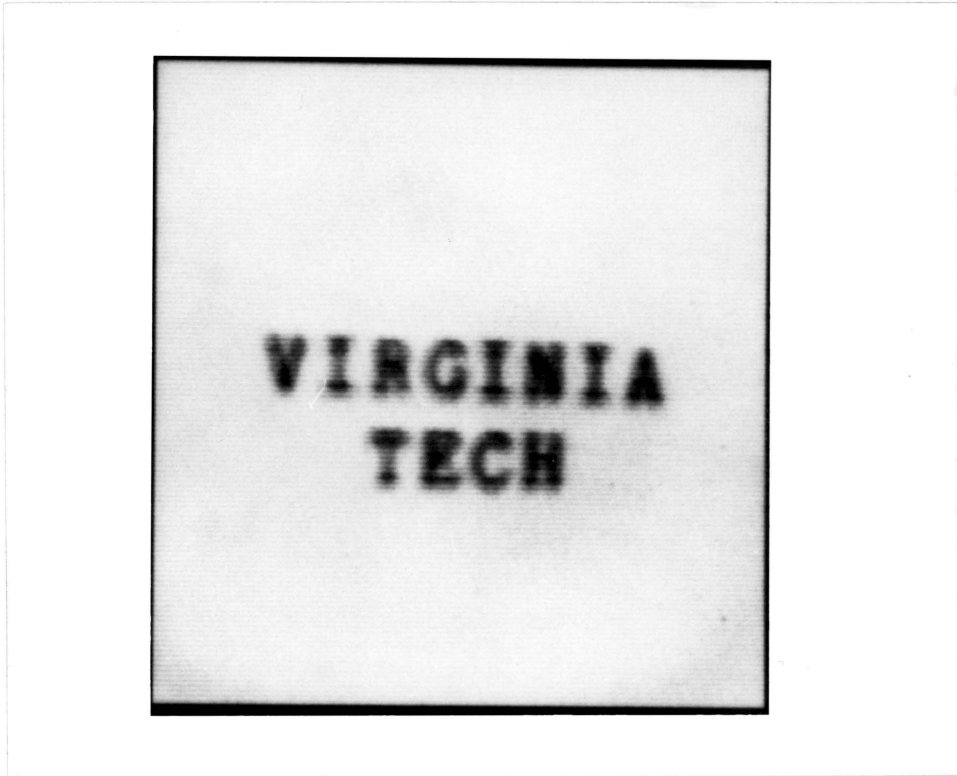


FIGURE 5.15: Out of focus text with annular.

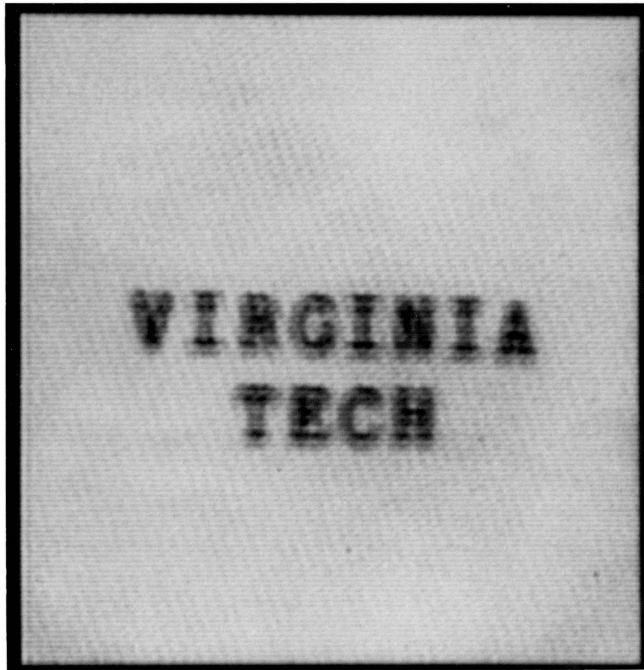


FIGURE 5.16: Out of focus text after filtering.

the letters were clearly detectable.

The severely out of focus system is shown in Fig. 5.17. An annular of  $e=0.472$  was used in forming the image shown in Fig. 5.18, where the results indicate that the system is performing a depth of field increase. The filtered version is then shown in Fig. 5.19. The filtered image denotes an interesting aspect of this system, and that is the annular aperture along with the annular-pass filtering can be used for shape detection and pattern recognition on out-of-focus images.



FIGURE 5.17: A severely out of focus text.

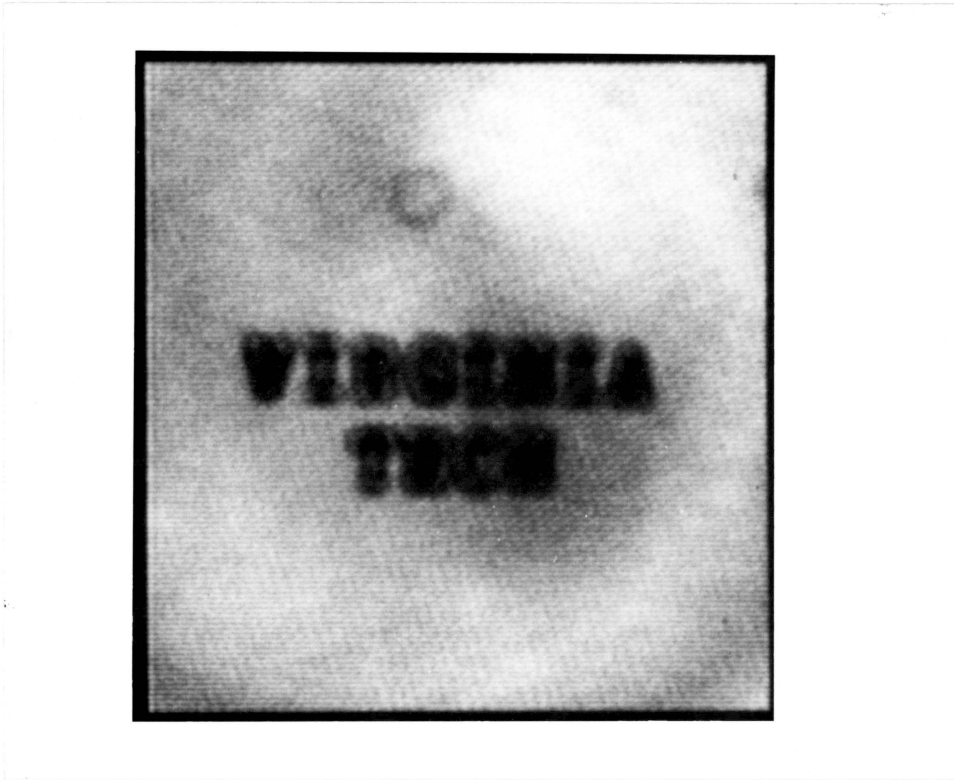


FIGURE 5.18: Severely out of focus text with annular.

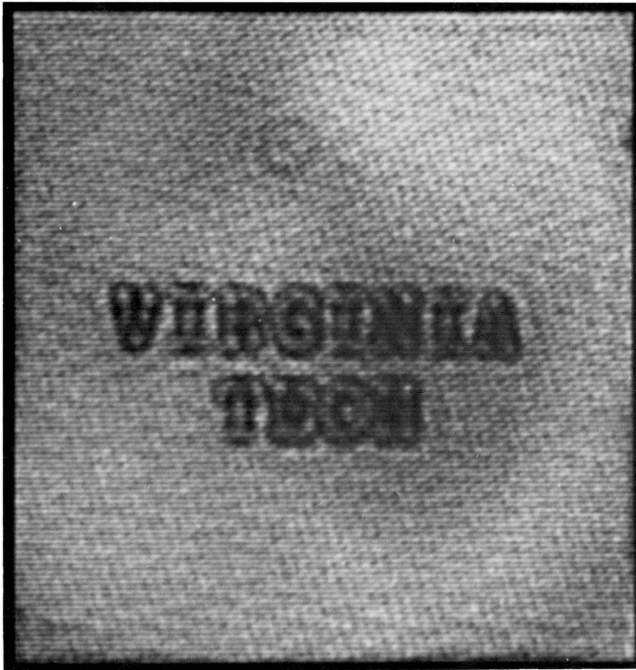


FIGURE 5.19: Severely out of focus text filtered.

## Chapter VI

### CONCLUSION

In conclusion, we have presented and demonstrated a hybrid technique to extend the depth of field of an incoherent imaging system. It was experimentally shown that the annular aperture indeed increases the depth of focus. The loss of image contrast was computer compensated by a non-ideal annular-pass filter.

The results indicate that with this technique the shape and the edges of the out of focus image can be recognized. The system can be used in applications where the depth of focus is essential, or where the shape preservation or recognition are important.

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APPENDIX A  
COMPUTER ROUTINES

The following RATFOR routines were used for the study of the increase in depth of field. These routines should be modified when used on systems other than GIPSY, since routines from the GIPSY directory are also called. The GIPSY routines are available at the Spatial Data Laboratory. In presenting these programs, it is assumed that the reader is familiar with Fortran programming.

A.1 The Fast Fourier Transform Routines

The following routines can be used in finding the discrete fourier transform of a two-dimensional array of points, such as an image, given that the array is N by N, where N is 2 to the power of an integer.

a. FFT Driver

```
#--FFTDRV          DRIVER
#
#IDENTIFICATION
#      TITLE          FFTDRV
#      VERSION        A.01
#      DATE           15 SEPT 1982
#      LANGUAGE       RATFOR
#      SYSTEM         VAX-11
#
#PURPOSE
#      DRIVER FOR COMMAND THAT PERFORMS THE RADIX-2 FAST
#      FOURIER
#      TRANSFORM OF A REAL IMAGE
```

```

#
#ENTRY POINT
#          FFTDRV (WORK,ERRET)
#
#ARGUMENT LISTING
#          WORK          INT          WORK ARRAY
#          ERRET         INT          ALTERNATE ERROR RETURN
#
#INCLUDE GIPCOM
#          MACA1         INCLUDE      GIPSY  TOKEN DEFINITIONS
#                                     FOR A1 CHARACTERS
#          GIPCOM
#          ERRET         INCLUDE      INCLUDE FILE FOR  COMMON
#                                     ERROR
#
#ROUTINES CALLED
#          PPUSH         PUSHES PROGRAM NAME INTO ERROR  STACK
#                                     (GIPSY)
#          PPOP          POPS PROGRAM NAME FROM ERROR STACK
#                                     (GIPSY)
#          RDKINL        OPEN A SIF AND FILL IN THE  IDENT
#                                     BLOCK
#          CLOSE         CLOSSES A FILE (GIPSY)
#          FFTALG        COMPUTES THE (INVERSE) FAST FOURIER
#                                     TRANSFORM (USER)
#
#*****
#
#INCLUDE MACA1
#SUBROUTINE FFTDRV (WORK,*)
#IMPLICIT INTEGER (A-Z)
#INCLUDE GIPCOM
#INCLUDE ERROR
#INTEGER IDENT (.IDLENGTH)
#DIMENSION WORK (.ARB)
#
#EQUIVALENCE (NPPL, IDENT (.IDNPPL))
#EQUIVALENCE (NLIN, IDENT (.IDNLINS))
#EQUIVALENCE (NCOL, IDENT (.IDNCOLS))
#EQUIVALENCE (NROW, IDENT (.IDNROWS))
#EQUIVALENCE (NBND, IDENT (.IDNBDS))
#EQUIVALENCE (MODE, IDENT (.IDMODE))
#
#CALL PPUSH ("FFTDRV")
#
#
#          OPEN INPUT FILE
#
#

```

```

CALL RDKINL (FDI1, IDENT, .OLD, IEV, %9999)
CALL CLOSE (FDI1)
#
#           CHECK INPUT FILE
#
IF (MODE ^= .REALMODE) GOTO 9000
M=1
NLIN2=NLIN/2
WHILE (NLIN2 > 1)
$(
M=M+1
NLIN2=NLIN2/2
$)
IF (NLIN ^= 2**M) GOTO 9020
N=1
NPPL2=NPPL/2
WHILE (NPPL2 > 1)
$(
N=N+1
NPPL2=NPPL2/2
$)
IF (NPPL ^= 2**N) GOTO 9020
NMAX=MAX (NPPL, NLIN)
#
#
NXT=1
ILIN1=GETWP (NXT, .REALMODE, NPPL)
ILIN2=GETWP (NXT, .REALMODE, NPPL)
XAR=GETWP (NXT, .REALMODE, 2*NMAX)
FTAR=GETWP (NXT, .REALMODE, 2*NLIN*NPPL)
#
IF (.OK ^= OSALOC (NXT)) GOTO 9010
#
CALL COMTIN (%9999)
#
#           CALL FFT ROUTINE
#
CALL
FFTALG (FDI1, FDO1, NBND, WORK (ILIN1), WORK (ILIN2), WORK (XAR),
        WORK (FTAR), NLIN, NPPL, NMAX, IEV, %9999)
#
CALL PPOP
#
RETURN
#
#           ERROR CONDITIONS
9000 CONTINUE

```

```

#
#           ILLEGAL DATA MODE
IEV=-2012
GOTO 9999
#
9010 CONTINUE
IEV=OSGIEV(IEV)
GOTO 9999
#
#           ILLEGAL ARRAY SIZE
9020 CONTINUE
IEV=-5004
GOTO 9999
#
9999 CONTINUE
CALL CLOSE(FDI1)
CALL CLOSE(FDO1)
#
RETURN 1
END

```

## b. FFT Algorithm

```

#--FFTALG           I/O &ALGORITHM
#
#IDENTIFICATION
#       TITLE           FFTALG
#       VERSION         A.01
#       DATE            15 SEPT 1982
#       LANGUAGE        RATFOR
#       SYSTEM          VAX-11
#
#PURPOSE
#       TO COMPUTE THE FAST FOURIER TRANSFORM (RADIX-2)
#       OF A SIF IMAGE (1 BND IF REAL, 2 BNDS IF COMPLEX)
#
#ENTRY POINT
#       FFTALG(FDI,FDO,NBND,ILIN1,ILIN2,XAR,FTAR,NLIN,NPPL,
#             NMAX,IEV,*)
#
#ARGUMENT LISTING
#       FDI             INPUT FILE DESCRIPTOR
#       FDO             OUTPUT FILE DESCRIPTOR
#       NBND           NO OF BANDS IN IMAGE TO BE PROCESSED
#       ILIN1          LINE BUFFER FOR REAL PART OF INPUT IMAGE
#       ILIN2          LINE BUFFER FOR IMAGINARY PART OF IMAGE

```

```

#          XAR          WORKARRAY
#          FTAR        WORKARRAY
#          NLIN        NO OF ROWS IN THE IMAGE
#          NPPL        NO OF COLUMNS IN THE IMAGE
#          NMAX        MAX OF NPPL AND NLIN
#          INV         INVERSE TRANSFORM IF TRUE
#          IEV         INTEGER EVENT VARIABLE
#          ERRET       ALTERNATE RETURN
#
#INCLUDE FILES/COMMONS
#          MACA1       INCLUDE (GIPSY)
#
#ROUTINES CALLED
#          PPUSH
#          PPOP
#          CLOSE
#          CPYIDR
#          COPYDS
#          RREAD
#          RWRITE
#          RX2FFT
#          DSCNAM
#
#*****
#
#INCLUDE MACA1
#SUBROUTINE FFTALG(FDI1,FDO1,NBND,ILIN1,ILIN2,XAR,FTAR,NLIN,
#                  NPPL,NMAX,IEV,*)
#IMPLICIT INTEGER (A-Z)
#CHARACTER FDI1(.FDLENGTH), FDO1(.FDLENGTH)
#INTEGER IDENT(.IDLENGTH), JDENT(.IDLENGTH)
#REAL ILIN1(NPPL), ILIN2(NPPL), NORM
#COMPLEX XAR(NMAX), FTAR(NLIN,NPPL)
#COMPLEX Z
#LOGICAL INV
#
#INCLUDE TTCOM
#
#CALL PPUSH("FFTALG")
#
#NMAX=MAX(NLIN,NPPL)
#FORWARD=1
#INVERSE=-1
#DFLT=1

```

```

CALL RNGETI ('FORWARD(1) OR INVERSE(-1) TRANSFORM?.',
            INVERSE, FORWARD, DFLT, VAR, IEV, %9000)
INV=.TRUE.
IF (VAR==1) INV=.FALSE.
#                               OPEN INPUTFILE
CALL CPYIDR(FDI1, IDENT, .OPNTMP, IEV, %9000)
#
#                               WRITE DESCRIPTOR RECORD TO TEMP FILE
CALL DSCNAM('FFTALG', IEV, %9000)
#
#                               SET UP OUTPUT FILE PARAMETERS
JDENT(.IDNPPL)=IDENT(.IDNPPL)
JDENT(.IDNLINS)=IDENT(.IDNLINS)
JDENT(.IDNCOLS)=IDENT(.IDNCOLS)
JDENT(.IDNROWS)=IDENT(.IDNROWS)
JDENT(.IDNBND)=2
JDENT(.IDMODE)=2
#
#AN INVERSE TRANSFORM MUST YIELD A REAL IMAGE FOR OUR
APPLICATION: NO. OF OUTPUT BANDS EQUALS 1
NOB=2
IF (INV) NOB=1
JDENT(.IDNBND)=NOB
#
#                               OPEN OUTPUT FILE
CALL COPYDS(FDO1, JDENT, IEV, %9000)
#
DO BLKN=1, NLIN
$(
CALL RREAD(FDI1, ILIN1, 1, BLKN, IDENT, .WAIT, IEV, %9000)
IF (NBND==2)
$(
CALL RREAD(FDI1, ILIN2, 2, BLKN, IDENT, .WAIT, IEV, %9000)
$)
ELSE
$(
DO I=1, NPPL
$(
ILIN2(I)=0.
$)
$)
IF (INV)
$(
DO J=1, NPPL
$(
XAR(J)=CMPLX(ILIN1(J), ILIN2(J))
XAR(J)=CONJG(XAR(J))

```

```

    $)
  $)
ELSE
  $(
    DO J=1,NPPL
      $(
        XAR(J)=CMPLX(ILIN1(J),ILIN2(J))
      $)
    $)
  CALL RX2FFT(XAR,NPPL)
  DO J=1,NPPL
    $(
      FTAR(BLKN,J)=XAR(J)
    $)
    $)
  NORM=FLOAT(NLIN*NPPL)
  DO J=1,NPPL
    $(
      DO I=1,NLIN
        $(
          XAR(I)=(FTAR(I,J))
        $)
      CALL RX2FFT(XAR,NLIN)
    IF(INV)
      $(
        DO I=1,NLIN
          $(
            FTAR(I,J)=CONJG(XAR(I))/NORM
          $)
        $)
      ELSE
        $(
        DO I=1,NLIN
          $(
            FTAR(I,J)=XAR(I)
          $)
        $)
        $)
    $)
  #
  DO BLKN=1,NLIN
    $(
    DO I=1,NPPL
      $(
        Z=FTAR(BLKN,I)
        ILIN1(I)=REAL(Z)
        ILIN2(I)=AIMAG(Z)
      $)
    $)
  $)

```

```

CALL RWRITE (FDO1, ILIN1, 1, BLKN, JDENT, .WAIT, IEV, %9000)
IF (NOB==1) GOTO 1000
CALL RWRITE (FDO1, ILIN2, 2, BLKN, JDENT, .WAIT, IEV, %9000)
1000 CONTINUE
$)
CALL PPOP
CALL CLOSE (FDI1)
CALL CLOSE (FDO1)
RETURN

```

```

#
#
#

```

ERROR CONDITIONS

```

9000 CONTINUE
CALL CLOSE (FDI1)
CALL CLOSE (FDO1)

```

```

#

```

```

9999 CONTINUE
9090 RETURN 1
END

```

### c. The Radix-2 Subroutine

```

#--RX2FFT      THIS IS A SUBROUTINE CALLED IN FFTALG.RAT
SUBROUTINE RX2FFT (X, N)
COMPLEX X(N), U, W, T
NV2=N/2
NM1=N-1
M=1
WHILE (NV2>1)
$(
M=M+1
NV2=NV2/2
$)
NV2=N/2
J=1
DO I=1, NM1
$(
IF (I>=J) GOTO 5
T=X(J)
X(J)=X(I)
X(I)=T
5 K=NV2
6 IF (K>=J) GOTO 7
J=J-K
K=K/2

```

```

GOTO 6
7 J=J+K
$)
PI=4.*ATAN(1.)
DO L=1,M
$(
LE=2**L
LE1=LE/2
U=CMPLX(1.,0.)
FLE1=FLOAT(LE1)
CARG=COS(PI/FLE1)
SARG=-1.*SIN(PI/FLE1)
W=CMPLX(CARG,SARG)
DO J=1,LE1
  $(
  DO I=J,N,LE
    $(
    IP=I+LE1
    T=X(IP)*U
    X(IP)=X(I)-T
    X(I)=X(I)+T
    $)
  U=U*W
  $)
$)
RETURN
END

```

## A.2 Filter Routines

The driver, algorithm, and subroutine used in the filtering procedure are as follows:

### a. Filter Driver

```

#--FILTRV          DRIVER
#
#IDENTIFICATION
#      TITLE          FILTRV
#      AUTHOR         MASOUD MOTAMEDI
#      VERSION        A.01
#      DATE           4 APRIL 1984
#      LANGUAGE       RATFOR
#      SYSTEM         VAX-11

```

```

#
#PURPOSE
#          DRIVER FOR COMMAND THAT PERFORMS THE BANDPASS
#FILTERING OF THE REAL AND IMAGENARY PARTS OF THE
#FOURIER TRANSFORM.
#ENTRY POINT
#          FFTDRV (WORK,ERRET)
#
#ARGUMENT LISTING
#          WORK          INT          WORK ARRAY
#          ERRET        INT          ALTERNATE ERROR RETURN
#
#INCLUDE FILES/COMMONS
#          MACA1        INCLUDE      GIPSY TOKEN DEFINITIONS
#          ERRET        INCLUDE      FOR A1 CHARACTERS
#                                     INCLUDE FILE FOR COMMON
#                                     ERROR
#
#ROUTINES CALLED
#          PPUSH        PUSHES PROGRAM NAME INTO ERROR STACK
#                                     (GIPSY)
#          PPOP         POPS PROGRAM NAME FROM ERROR STACK
#                                     (GIPSY)
#          RDKINL      OPEN A SIF AND FILL IN THE IDENT
#                                     BLOCK
#          CLOSE        CLOSSES A FILE(GIPSY)
#
#*****
#
#INCLUDE MACA1
#SUBROUTINE FILDRV(WORK,*)
#IMPLICIT INTEGER (A-Z)
#INCLUDE GIPCOM
#INCLUDE ERROR
#INTEGER IDENT(.IDLENGTH)
#DIMENSION WORK(.ARB)
#
#EQUIVALENCE(NPPL,IDENT(.IDNPPL))
#EQUIVALENCE(NLIN,IDENT(.IDNLINS))
#EQUIVALENCE(NCOL,IDENT(.IDNCOLS))
#EQUIVALENCE(NROW,IDENT(.IDNROWS))
#EQUIVALENCE(NBND,IDENT(.IDNBND))
#EQUIVALENCE(MODE,IDENT(.IDMODE))
#
#CALL PPUSH("FILDRV")
#

```

```
# OPEN INPUT FILE
#
CALL RDKINL(FDI1,IDENT,.OLD,IEV,%9999)
CALL CLOSE(FDI1)
#
# CHECK INPUT FILE
#
IF (MODE^=.REALMODE) GOTO 9000
M=1
NLIN2=NLIN/2
WHILE (NLIN2>1)
$(
M=M+1
NLIN2=NLIN2/2
$)
IF (NLIN^=2**M) GOTO 9020
N=1
NPPL2=NPPL/2
WHILE (NPPL2>1)
$(
N=N+1
NPPL2=NPPL2/2
$)
IF (NPPL^=2**N) GOTO 9020
NMAX=MAX(NPPL,NLIN)
#
#
NXT=1
ILIN1=GETWP(NXT,.REALMODE,NPPL)
ILIN2=GETWP(NXT,.REALMODE,NPPL)
#
IF (.OK^=OSALOC(NXT)) GOTO 9010
#
CALL COMTIN(%9999)
#
#
CALL FILALG(FDI1,FDO1,NBND,WORK(ILIN1),WORK(ILIN2),
NLIN,NPPL,NMAX,IEV,%9999)
#
CALL PPOP
#
RETURN
#
# ERROR CONDITIONS
9000 CONTINUE
#
# ILLEGAL DATA MODE
```



```

#       XAR           WORKARRAY
#       FTAR          WORKARRAY
#       NLIN          NO OF ROWS IN THE IMAGE
#       NPPL          NO OF COLUMNS IN THE IMAGE
#       NMAX          MAX OF NPPL AND NLIN
#       INV           INVERSE TRANSFORM IF TRUE
#       IEV           INTEGER EVENT VARIABLE
#       ERRET        ALTERNATE RETURN
#
#INCLUDE FILES/COMMONS
#       MACA1         INCLUDE (GIPSY)
#
#ROUTINES CALLED
#       PPUSH
#       PPOP
#       CLOSE
#       CPYIDR
#       COPYDS
#       RREAD
#       RWRITE
#       RX2FFT
#       DSCNAM
#
#*****
#
#       INCLUDE MACA1
#       SUBROUTINE
FILALG(FDI1,FDO1,NBND,ILIN1,ILIN2,NLIN,NPPL,NMAX,IEV,*)
#       IMPLICIT INTEGER (A-Z)
#       CHARACTER FDI1(.FDLENGTH), FDO1(.FDLENGTH)
#       INTEGER IDENT(.IDLENGTH), JDENT(.IDLENGTH)
#       REAL ILIN1(NPPL), ILIN2(NPPL), NORM
#       REAL VAR2,GAIN,VAR3
#
#       INCLUDE TTCOM
#
#
#       CALL PPUSH("FILALG")
#
#       NMAX=MAX(NLIN,NPPL)
#       CALL  RNGETI("INPUT THE INNER RADIUS",1,128,128,VAR,
#                   IEV,%9000)
#       CALL  RNGETI("INPUT THE OUTER RADIUS",1,128,1,VAR1,IEV,
#                   %9000)
#       CALL  RNGETR("VALUE OF THE STOPBAND",0.0,10.0,0.0,VAR2,
#                   IEV,%9000)

```

```

CALL  RNGETR("THE GAIN IN THE PASSBAND",0.0,10.0,0.0,
            VAR3,IEV,%9000)
#
#           OPEN INPUT FILE
CALL  CPYIDR(FDI1,IDENT,.OPNTMP,IEV,%9000)
#
#           WRITE DESCRIPTOR RECORD TO TEMP FILE
#
#           CALL DSCNAM('FILALG',IEV,%9000)
#
#           SET UP OUTPUT FILE PARAMETERS
#
#           JDENT(.IDNPPL)=IDENT(.IDNPPL)
JDENT(.IDNLINS)=IDENT(.IDNLINS)
JDENT(.IDNCOLS)=IDENT(.IDNCOLS)
JDENT(.IDNROWS)=IDENT(.IDNROWS)
JDENT(.IDNBND)=2
JDENT(.IDMODE)=2
#
NOB=3
GAIN=VAR2
#
#           OPEN OUTPUT FILE
CALL  COPYDS(FDO1,JDENT,IEV,%9000)
#
DO  BLKN=1,NLIN
$(
CALL  RREAD(FDI1,ILIN1,1,BLKN,IDENT,.WAIT,IEV,%9000)
IF(NBND>1)
$(
CALL  RREAD(FDI1,ILIN2,2,BLKN,IDENT,.WAIT,IEV,%9000)
$)
ELSE
$(
DO  I=1,NPPL
$(
ILIN2(I)=0.
$)
$)
DO  I=1,NPPL
$(
IF  (BLKN<=128)
$(
IF  (I<=128)
$(
NORM=(BLKN**2+I**2)**0.5
CALL  SET(NORM,ILIN1(I),ILIN2(I),VAR,VAR1,GAIN,
          VAR3)

```

```

    $)
ELSE
    $(
    IF (I>128)
        $(
        NORM=(BLKN**2+(NPPL-I)**2)**0.5
        CALL SET(NORM,ILIN1(I),ILIN2(I),VAR,VAR1,GAIN,
                VAR3)
        $)
    ELSE
        $(
        ILIN1(I)=0.
        ILIN2(I)=0.
        $)
    $)
ELSE
    $(
    IF (BLKN>=128)
        $(
        IF (I<=128)
            $(
            NORM=(I**2+(NLIN-BLKN)**2)**0.5
            CALL SET(NORM,ILIN1(I),ILIN2(I),VAR,VAR1,GAIN,
                    VAR3)
            $)
        ELSE
            $(
            IF (I>=128)
                $(
                NORM=((NPPL-I)**2+(NLIN-BLKN)**2)**0.5
                CALL
SET(NORM,ILIN1(I),ILIN2(I),VAR,VAR1,GAIN,
        VAR3)
                $)
            ELSE
                $(
                ILIN1(I)=0.
                ILIN2(I)=0.
                $)
            $)
        $)
    ELSE
        $(
        ILIN1(I)=0.
        ILIN2(I)=0.
        $)

```



APPENDIX B  
CAMERA LENS

In using a camera lens as the optical system of the incoherent image processing system, extreme care must be taken. The lenses characteristics is limited first of all by its focal length. If the focal length is very small, then the objects which are very close to the lens can be brought into focus. This makes the resolution very limited at large distances. On the other hand, a lens with a large focal length has limited resolution at short distances.

In the study of the effect of the annular aperture in increasing the depth of field, the characteristics of the system is highly dependent on the focal length and the actual size of the aperture stop. It is therefore important that these two quantities are known exactly for the lens used. If a lens with a small focal length is to be used, extreme care must be taken in choosing the size of the annular aperture so that the annular does not create a shadow on the image. In other words, if the annular's size is more than a calculated maximum, then a dark shadow will be present on the image which effectively corresponds to a loss of information. It should be mentioned that the annular is effectively put at the rim of the light blocker

of the lens, therefore the effective size of the annular is the size seen from an object point on the effective position of the lens.

To further clarify this discussion, consider the lens shown in Fig. B.1. The ray of light, from the point source, passing the rim of the annular aperture will pass the lens at a point which corresponds to the effective size of the annular, therefore the effective size is larger than the actual size of the annular. The maximum allowable size for the annular aperture can also be found from the same figure. It is obvious that a ray that hits the peak of the opening of the lens, i.e., the highest possible point of the opening, will create the maximum allowable angle with the horizontal line, therefore an annular aperture that can create this angle has the maximum allowable size. If the distance between the object and the rim of the light breaker is denoted by  $d$  and the distance from the rim to the center of the lens is given by  $s$ , then the maximum allowable size for the annular can be found using:

$$\text{TAN } B_{\text{max}} = \frac{D}{2(d + s)}, \quad (\text{B.1})$$

where  $D$  is the aperture stop opening. However, the maximum annular size,  $b_{\text{max}}$ , will give the same angle, or:

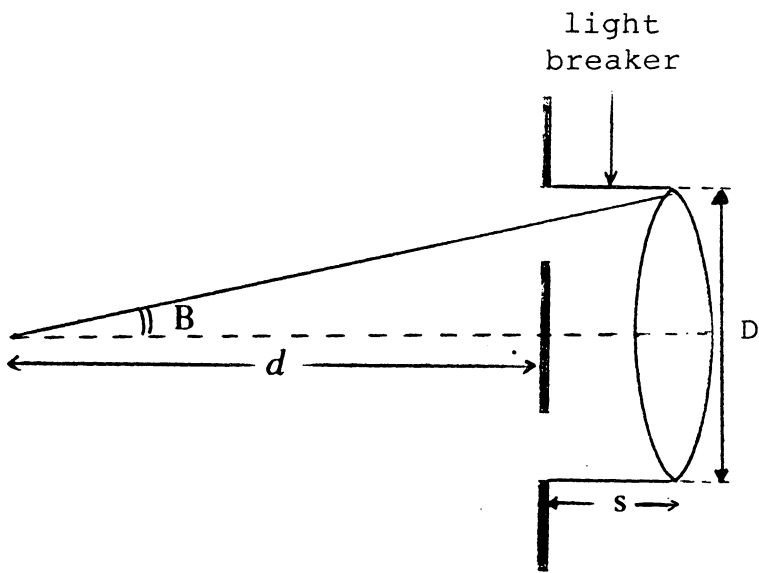


FIGURE B.1: The actual positioning of the annular aperture.

$$\text{TAN } B_{\text{max}} = \frac{b_{\text{max}}}{2d}, \quad (\text{B.2})$$

and equating (B.1) with (B.2), the maximum annular size will be found to be:

$$b_{\text{max}} = \frac{d \cdot D}{D + s}. \quad (\text{B.3})$$

If the limit for the size is not met, the rays of light will all hit the side of the light blocker and no light is transmitted and the information is lost.

The point that should be mentioned once again is that in all of the calculations for the annular size, the effective lens, effective aperture stop, and the effective focal point should be used so that the results derived from a single-lens system could be employed.

## APPENDIX C

### IMAGE PREPARATION

The optical/digital image processing system operates on the images that are saved in the magnetic tape storage. These stored images are the images observed by the camera unit and then digitized by the VICOM image processing routines. The VICOM system digitizes the observed image into a 512 by 512 array of pixels, where the pixels do not have a physical measurement, however, by using the magnification of the lens and the actual size of the object, a length can be assigned to each pixel if needed.

The digitization process will elongate the object by a factor of four to three, therefore a vertical compression is required in bringing in the actual size as observed by the lens. The command XPCMP will do the compression after the proper values are inputted.

The size of the digitized image is 512 by 512, as was mentioned before, and the image is saved as a Binary array, therefore in order to do a fast Fourier transforming on the image, one should first change the array to a Real-valued array by using the command MODCH, and then cut the portion of the image that is needed using the command SBIMG. This cutting procedure is due to the memory limitations of the

system; the fast Fourier transform routines require large quantity of memory.

If the image is to be displayed on a TV monitor, the DSPLY command can be used once a light device is allocated to the user. If a plot of the transform is needed, the PLTSUR command will plot a magnitude profile either on an allocated TV monitor or on the HP plotter.

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AN OPTICAL/DIGITAL INCOHERENT IMAGE PROCESSING SYSTEM  
FOR AN EXTENDED DEPTH OF FIELD

by

Masoud Motamedi

ABSTRACT

A severely defocused incoherent system has isolated zeros in its optical transfer function (OTF); therefore, an exact inverse filtering cannot be performed. It has been established that, by using an annular aperture in an optical system, the depth of focus can be extended. Isolated zeros in the OTF can therefore be avoided by choosing an annular aperture with a proper radius ratio. However, in the process of increasing the depth of focus of the system, this method results in a loss of image contrast. An annular pass filter can be used to restore this loss in contrast. A simple hybrid optical/digital image processing system in which a TV camera is coupled with an annular aperture is considered. The annular-pass filtering to compensate the loss of contrast is performed by a digital computer. The experimental results are presented.