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TWO POINT RESOLUTION OF A DEFOCUSED MULTI-APERTURE SYSTEM EYELET

BY

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THESIS

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ABSTRACT

Multi-aperture optical systems based on the insect eye offer an alternative to the common optical system based on the human eye. Some of the advantages of a multi-aperture system include the ability to perform parallel processing, have super resolution and have available large amounts of system redundancy.

An individual eyelet of a multi-aperture system consists of a gradient index lens coupled to optical fibers which transfer the incident light on the lens to individual detectors.

A mathematical model of an individual eyelet was developed. It is a flexible model allowing various system parameters to vary. Computer based algorithms were developed to locate and resolve two points in space. The model was exercised with experimental data and found to have a resolution of 3.1°. The algorithm was also exercised with the computer model and the results compared favorably.

ACKNOWLEDGMENTS

I have learned, from experience, over the last six months that a graduate thesis is a team effort. The completion of this research would not have been possible without support and I would like to thank:

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My wife, Jan, who accepted my need to spend nights and weekends studying.

My parents who instilled the importance of an education.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

Insect Eye

Almost all conventional imaging systems are patterned after a human eye; a single large aperture optical system coupled to a large number of detectors to obtain an image. Since each detector is addressed individually, a large amount of time and processing is required for image formation or analysis. In contrast, consider an optical system modeled after the insect eye, a multi-aperture optical system. Insect eyes have an extremely wide field-of-view, as much as 270 degrees. It has been shown that most insect eyes cannot image an object.(1) However, the insect eye is optimized for performing certain tasks such as locating and tracking a target (searching for food, mating, normal flight and defense). The insect eye also processes in parallel; therefore, a short amount of time is required to perform certain tasks.

Most entomologists subscribe to the theory that there are two types of insect eyes, the apposition eye and the superposition eye. In the apposition eye, each eyelet has a small field of view that overlaps with the neighboring eyelets. The sensed information is reconstructed in the brain from tiny segments of information obtained by each eyelet. The superposition eye is based on the superposition principle; the actual image is formed from a layer of images that are superimposed.(2)

The single eyelet or omatidia is shown in Figure 1.(2) The omatidia consists of 3 distinct structures: (1) lens system (corneal lens and the crystalline cone); (2) a rhabdom which acts like a detector and converts the light to an electric signal; and (3) a transparent, hose-like medium to transfer the light. The omatidia is surrounded by pigment cells which serve as optical insulation between neighboring eyelets.(2) Some insects have up to 20,000 of such eyelets. The most important items learned from insect physiology are: (1) an insect does not need to form an image to perform complex tasks; and (2) multi-aperture systems are perfect platforms for application of parallel processing.(3)

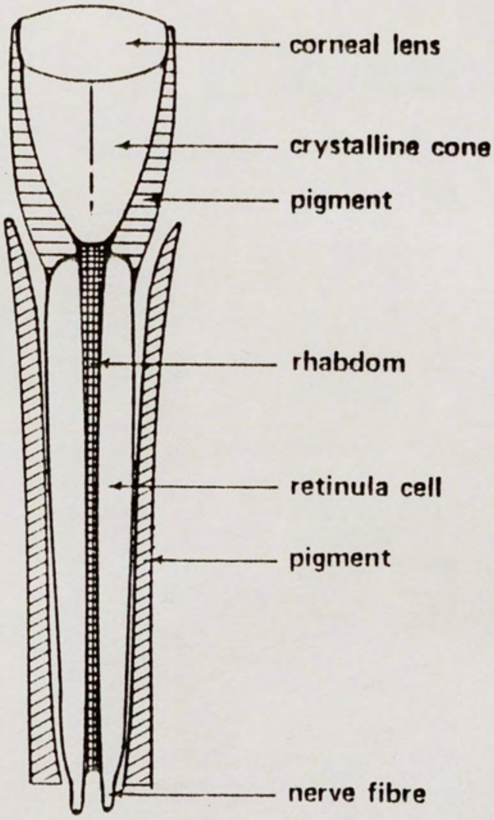

Figure 1. Single Eyelet (Basic Omatidia)

Multi-Aperture Optical System

To develop a multi-aperture optical system it is not necessary to emulate the insect eye, but use it as a guide to assemble a system to perform certain tasks. It is important to remember that an image is not required to perform many tasks.

Some typical characteristics of a multi-aperture optical system are:

1) super resolution capability
2) parallel processing
3) built-in redundancy

There are three general configurations for multi-aperture optical systems.(4)

1) Those that superimpose the image from each lens; i.e., one generates an image from overlapping images from each lens.
2) Those that place each lens in apposition; i.e., each lens has a unique field of view, where their fields of view overlap by a fixed prescription.
3) Those that discard the unified optical image and spacially sample the field of view. Reconstruction of the image information is done by calculational techniques and no alignment is necessary.

The third configuration is the only system considered, since it requires no alignment and is extremely simple to construct.

A random apposition multi-aperture optical system consists of a set of lenses focused onto pixel dividers. This system was first described by

Walters.(4) The lenses are gradient index lenses and the pixel dividers are step index optical fibers. A characteristic of this system is that any point of a concentric circle in space, viewed by a pixel, has a unique detector response.(3)

Kellog(5) compared the resolution and detection characteristics of multi-aperture vs. single aperture systems, and concluded that a multi-aperture system resolution improves by the square root of the number of overlapping pixels. Mathews(6) has shown that overlap can be controlled with excellent statistical results and need not be carefully aligned into place. Walters(4) has described the data path in mathematical nomenclature as a set of array operators.

The conventional optical system utilized for point source detection and location usually employs a quadrant detector placed at the focal plane of the system. The quadrant detector divides the focal plane into four quadrants. The object point location is determined by differencing the output signals from the detectors on each side of the axis of interest.

Consider utilizing a single eyelet of a multi-aperture optical system defocused to provide the field of view redundancy. A single Gradient Index (GRIN) lens is used with 16 optical fibers arranged in a hexagonal array and placed far enough out of the focal plane to allow at least three fibers to be illuminated by a single object point. The output from the three fibers can be utilized to determine the point source location in azimuth and elevation with respect to the GRIN lens optical axis. The single eyelet is shown in Figure 2.

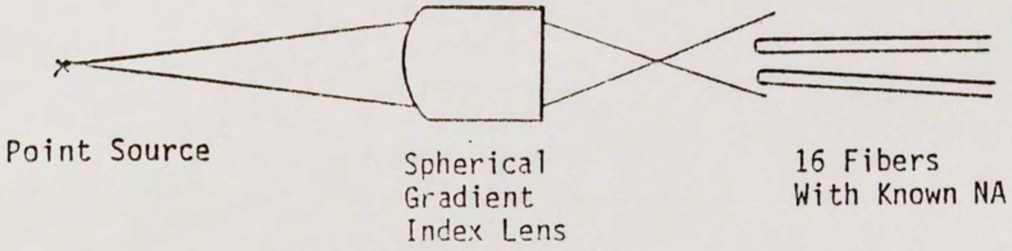

Figure 2. Basic Multi-Aperture Eyelet

The purpose of this study was to mathematically model a GRIN eyelet similar to the experimental hardware developed at the University of Central Florida by Dr. R. Walters. The configuration shown in Figure 2 was utilized to characterize the eyelet. A source model, GRIN model and fiber model were developed to simulate the eyelet.

CHAPTER TWO

THE EYELET MODEL

A mathematical eyelet model allows the system designer to change certain aspects of his system to determine their effects in a fast and efficient manner without changing actual hardware.

The eyelet model is composed of three submodels, a point source, a gradient index lens, and optical fibers.

Ray matrix optics is used to propagate the point source through the system to the fiber plane, locate the centroid and define the spot size. Separate intensity models have been developed to determine the intensity distribution due to the point source. The ray matrix models and intensity models are discussed in detail in the following sections.

The Source

The point source model is allowed to vary in divergence, wavelength, position (azimuth, elevation and distance from the GRIN lens).

Consider a point source located in the field of view of the GRIN lens. To determine the photon flux collected by the GRIN lens, the geometry of Figure 3 is used.

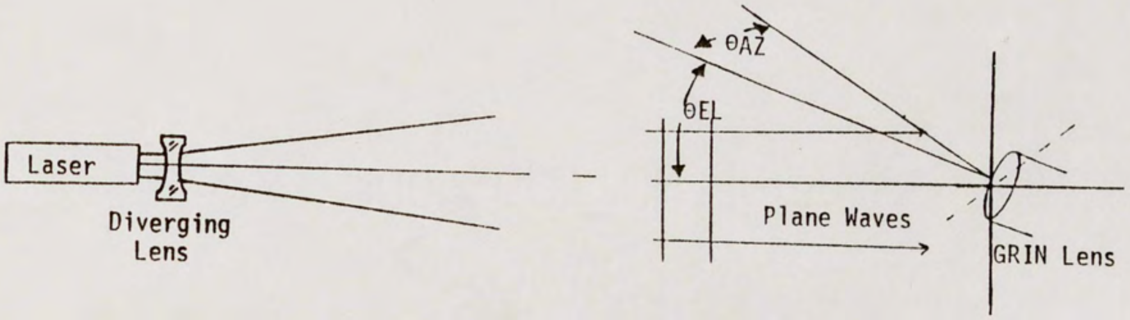

Figure 3. Geometry of Source and GRIN Lens

The total power received by the entrance aperture of the GRIN lens is given by:(7)

$$P = EACOS\Theta_{AZ}COS\Theta_{EL} \tag{1}$$

where

P = power collected by GRIN lens (watts)
E = irradiance of the source (watts/cm^2)
A = area of GRIN lens aperture (cm^2)
Θ_{AZ} = azimuth angle
Θ_{EL} = elevation angle

The derivation of equation 1 is given in Appendix A.

The irradiance of the source can be determined by the intensity of the source and the range from source to GRIN lens.

$$E = \frac{I}{R^2} \tag{2}$$

where

I = intensity of source (watts/sr)

R = range from source to GRIN lens (cm^2)

Consider the geometry of Figure 3 to calculate the intensity of the source.(8) Intensity of a source is given by

$$I = \frac{P_L}{\Omega} \tag{3}$$

where

P_L = power of laser in watts

Ω = solid angle of laser beam with diverging lens in steradians

The assumptions made in the model are that the laser is placed far enough from the GRIN lens that a diverging lens placed in front of the laser fills the GRIN lens with a uniform plane wave.

The total power received by the GRIN lens aperture is found by substituting equations 2 and 3 into equation 1.

$$P = \frac{P_L A \cos\Theta_{AZ} \cos\Theta_{EL}}{\Omega R^2} \tag{4}$$

where

P = watts collected by the GRIN lens,

Substituting in the equations for the lens area and solid angle of the laser, the power, P, becomes

$$P = \frac{P_L \pi r^2 \cos\Theta_{AZ} \cos\Theta_{EL}}{4\pi \sin^2(\Theta_D/2) R^2}\,\tau \tag{5}$$

where

A = has been replaced by πr^2 and r is the lens radius

Ω = $4\pi \sin^2(\Theta_D/2)$ where Θ_D is the laser beam and diverging lens divergence angle

and

τ = transmission of diverging lens

Coupled into τ, are the estimates of fresnel losses in the optical train.

In review, P is the power transferred from a point laser and diverging lens source to a lens with collecting area A with Θ_{AZ}, Θ_{EL} being the position of the point source with respect to the optical axis of the GRIN lens.

The ray matrix model to propagate the rays from the point source to the front of the GRIN lens is a simple transfer matrix.(9)

$$\begin{bmatrix} r_1 \\ \theta_1 \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} r_s \\ \theta_s \end{bmatrix} \qquad (6)$$

where

r_1 = ray height at lens

θ_1 = ray angle at lens

d = distance from source to lens

r_s = ray height at source

θ_s = ray angle at source

Rays are traced from the point source to the optical fibers to locate and define the center of the spot image on the front face of the fibers.

The GRIN Lens

The gradient index lens is a glass rod whose refractive index decreases quasi-quadratically from the axis to the periphery along the radius.(10)

In the model the lens is allowed to vary in index of refraction, length, diameter, pitch, and numerical aperture (NA) and also have a flat or spherical radius on one end.

The profile of the refractive index can be expressed by:

$$n(r) = n_0(1-\frac{Ar^2}{2}) \qquad (7)$$

where

A = quadratic constant

r = radial variable

n_0 = on axis index of refraction

A typical refractive profile is shown in Figure 4.

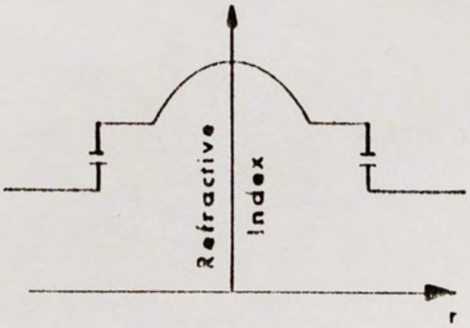

Figure 4. Radial Refractive Index Profile

The ray matrix equations that characterize a spherical GRIN lens are:

$$\begin{bmatrix} r_2 \\ \\ \Theta_2 \end{bmatrix} = \begin{bmatrix} \mathrm{COS}(\sqrt{A}Z) - \dfrac{Q_1}{No\sqrt{A}}\,\mathrm{SIN}(\sqrt{A}Z) & \dfrac{1}{No\sqrt{A}}\,\mathrm{SIN}(\sqrt{A}Z) \\ \\ -(Q_1\mathrm{COS}(\sqrt{A}Z) + No\sqrt{A}\,\mathrm{SIN}(\sqrt{A}Z)) & \mathrm{COS}(\sqrt{A}Z) \end{bmatrix} \begin{bmatrix} r_1 \\ \\ \Theta_1 \end{bmatrix} \quad (8)$$

where

r_1 = distance between incident ray and optical axis

Θ_1 = incident angle in radians

A = quadratic constant

Z = lens length

No = on-axis index of refraction

r_2 = distance between exiting ray and optical axis

Θ_2 = exiting ray angle i radians

R = radius of curvature of GRIN lens

Q_1 = $(No-1)/R$

Figure 5 shows this relationship graphically.

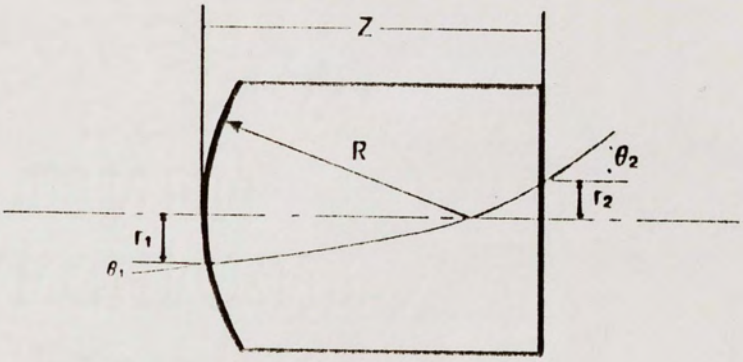

Figure 5. GRIN Lens Input And Output Notation

If a flat lens is used, $Q_1 = 0$, the equations reduce to the more familiar

$$\begin{bmatrix} r_2 \\ \Theta_2 \end{bmatrix} = \begin{bmatrix} \mathrm{COS}(\sqrt{A}Z) & \frac{1}{No\sqrt{A}}\,\mathrm{SIN}(\sqrt{A}Z) \\ -No\sqrt{A}\,\mathrm{SIN}(\sqrt{A}Z) & \mathrm{COS}(\sqrt{A}Z) \end{bmatrix} \begin{bmatrix} r_1 \\ \Theta_1 \end{bmatrix} \tag{9}$$

In the experimental device a 3mm diameter, quarter-pitch flat GRIN lens was used. For a quarter-pitch GRIN lens, $\sqrt{A}Z$ is equal to $\pi/2$ and the ray matrix equations reduce to equations 10 and 11.

$$r_2 = \frac{\Theta_1}{No\sqrt{A}} \tag{10}$$

$$\Theta_2 = -No\sqrt{A}r_1 \tag{11}$$

From equation 10 it is evident that r_2 is not dependent on r_1, and all parallel rays entering the quarter pitch GRIN lens focus to one point on the rear surface of the lens. Therefore, the focal plane is located at the rear surface of the lens, with a focal length defined by

$$f = \frac{1}{No\sqrt{A}SIN(\sqrt{A}Z)} \tag{12}$$

To determine the intensity distribution of the monochromatic light beam either at the focal plane of the GRIN lens, or out of the focal plane, the following diffraction integral for intensity and phase is utilized.(11)

$$U(x_0,y_0) = \frac{exp(jkz)}{j\ z}\ exp[jk/2z(x_0{}^2+y_0{}^2)\iint_{-\infty}^{\infty}\Big\{U(x_1,y_1)\ exp[j\frac{k}{2z}\ (x_1{}^2+y_1{}^2)]\Big\}exp[-j\frac{2\pi}{\lambda z}(x_0x_1+y_0y_1)]dx_1dy_1 \tag{13}$$

where

$k = 2\pi/\lambda$

z = distance from aperture to observation region

λ = wavelength

The coordinates for this equation are defined in Figure 6.(11)

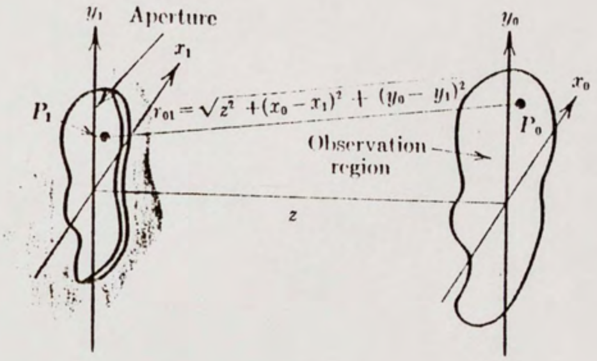

Figure 6. Diffraction Geometry

Since we are only concerned with intensity, which is given by UU*, we can ignore the phase components outside the integrand and re-write equation 13.

$$U(x_0,y_0)= \frac{A}{j\ z}\iint_{-\infty}^{\infty} t(x_1,y_1)\exp[-jk/2f(x_1{}^2+y_1{}^2)]\exp[jk/2z(x_1{}^2+y_1{}^2)]$$

$$\exp[-j^2\pi/\lambda_Z(x_0x_1,+y_0y_1)]dx_1,dy_1] \qquad (14)$$

or rearranging terms

$$U(x_0,y_1)= \frac{A}{j\lambda Z}\iint_{-\infty}^{\infty} [t(x_1,y_1)\exp[jk/2(x_1{}^2+y_1{}^2)(\frac{1}{Z} - \frac{1}{f})]$$

$$\exp[-j2\pi/\lambda Z(x_0x_1+y_0y_1)]dx_1dy_1] \qquad (15)$$

let $\varepsilon = \frac{1}{Z} - \frac{1}{f}$

where f = focal length of the lens

A = electric field amplitude

(and equation 14 becomes)

$$U(x_0,y_0) = \frac{A}{j\lambda z}\iint_{-\infty}^{\infty} [t(x_1,y_1)\exp[(jk/2)\varepsilon(x_1^2+y_1^2)] \tag{16}$$

$$\exp[-j^2\pi/\lambda_z(x_0x_1 + y_0y_1)]dx_1dy_1]$$

From equation 16, $U(x_0,y_0)$ is found as a Fourier transform of $t(x_1,y_1)$ $\exp[k/2)\varepsilon(x_1^2+y_1^2)]$ where the transform must be evaluated at frequencies ($f_x = \frac{x_0}{\lambda z}$, $fy = \frac{y_0}{\lambda z}$) to assure correct space scaling in the observation plane.

When ε goes to zero, i.e. the observation plane is the focal plane, equation 16 gives the Fraunhofer diffraction integral and when ε is finite, equation 16 gives the Fresnel integral.

Now letting

$$\exp[(jk/2)\varepsilon(x_1^2+y_1^2)]=g(x,y)$$

$$fx = \frac{x_0}{\lambda Z} \quad \& \quad fy = \frac{y_0}{\lambda Z} \qquad x_1 = x \ \& \ y_1 = y$$

Equation 16 becomes

$$U(x_0,y_0) = \frac{A}{j\lambda z}\iint_{-\infty}^{\infty} g(x,y)\exp[-j2\pi(xfx+yfy)]dxdy \qquad (17)$$

To exploit the circular symmetry of the GRIN lens, the transform to polar coordinates is accomplished by

$$\begin{array}{ll} r = \sqrt{x^2+y^2} & x = r\text{COS}\,\Theta \\ \Theta = \tan^{-1}(y/x) & y = r\text{SIN}\,\Theta \\ \rho = \sqrt{fx^2+fy^2} & fx = \rho\,\text{COS}\,\Theta \\ \phi = \tan^{-1}(fy/fx) & fy = \rho\,\text{SIN}\,\phi \end{array}$$

Applying the coordinate transformations to Equation 17;

$$U(r) = \frac{A}{j\lambda z}\int_0^{2\pi} d\Theta\int_0^{\infty} dr.r\ g(r)\exp[-j2\pi r\rho\text{COS}\Theta\text{COS}\phi+\text{SIN}\Theta\text{SIN}\phi]$$

or (18)

$$\frac{A}{j\lambda z}\int_0^{2\pi} dr\cdot r\ g(r)\int_0^{2\pi} d\Theta\exp[-j2\pi r\rho\ \text{COS}(\Theta-\phi)]$$

where

$$g(r)=\exp[jk\varepsilon r^2/_2] \text{ and}$$

$$Jo(a) = \frac{1}{2\pi}\int_0^{2\pi} \exp[-ja\text{COS}(\Theta-\phi)]d\Theta$$

So rewriting equation 18

$$U(r) = \frac{A2\pi}{j\lambda z} \int_0^\infty rg(r)Jo(2\pi r\rho)dr$$

For a circular aperture t(r) = circ (r)

where

$$circ(r) = \begin{cases} 1 & R \leq 1 \\ 0 & \text{Otherwise} \end{cases}$$

Equation 18 becomes

$$U(r) = \frac{A2\pi}{j\lambda z} \int_0^R r\ \exp(jk\varepsilon r^2/2)Jo(2\pi r\rho)dr \tag{19}$$

To simplify the integral let

$$\alpha = \frac{k\varepsilon r^2}{2} \ \& \ \beta = 2\pi\rho$$

Substituting into Equation 19: $A = P^{1/2}$

where P is the power injected into the lens (equation 5)

$$\text{and} \quad \exp[jk\varepsilon r^2/2] = COS(k\varepsilon r^2/2) + jSIN(k\varepsilon r^2/2) \tag{20}$$

$$U(r) = P^{1/2}\,\frac{2\pi}{j\lambda z}\int_0^R r(\mathrm{COS}\alpha + j\mathrm{SIN}\alpha)Jo(\beta r)dr$$

using a change of variables

$$r_1 = \beta r \text{ and } dr_1 = \beta dr \tag{21}$$

$$U(r_1/\beta) = \frac{P^{1/2}\,2\pi}{j\lambda z\beta^2}\int_0^{\beta R} r_1(\mathrm{COS}\ + \mathrm{SIN}\ )Jo(r_1)dr_1$$

so

$$U(r_1/\beta) = \frac{P^{1/2}\,2\pi}{j\lambda z\beta^2}\left[\int_0^{\beta R} r_1\mathrm{COS}\alpha Jo(r_1)dr_1 + j\int_0^{\beta R} r_1\mathrm{SIN}\alpha Jo(r_1)dr_1\right] \tag{22}$$

In the simplifying case where the observation plane is the focal plane, (where $\varepsilon = 0$, now contained in α) and equation 22 reduces to equation 23

$$U(r_1/\beta) = \frac{P^{1/2}\,2\pi}{j\lambda z\beta^2}\int_0^{\beta R} r_1 Jo(r_1)dr_1 \tag{23}$$

which reduces upon integration to the familiar Fraunhofer intensity distribution referred to as the Airy Pattern

$$I = P\left(\frac{KR}{Z}\right)^2\left(\frac{J_1(2\pi\rho R)^2}{2\pi\rho}\right) \tag{24}$$

When the observation plane is not the focal plane numerical integration is performed on equation 22 using the trapezoid method to determine the intensity at the input plane of the fibers.

The Optical Fiber

The optical fiber unit that was modeled is multimode. The fibers can be placed either at the focal plane of the GRIN lens or out of the focal plane at another observation plane.

The assumptions made in the fiber model are:

1) The fibers are parallel to optical axis
2) The illuminated single fiber is uniform in core index

The model does not constrain the numbers of fibers that can be used. The fibers are stored in an (x,y) grid in the image space with (o,o) being the optical axis. Two different alignments containing 16 fibers placed in square and hexagonal array patterns are shown in figures 7 and 8 respectfully. It should be noted that a symmetrical array is not required, random placement is acceptable.

The ray matrix equation used to transfer the rays from the rear of the lens to the fiber plane is

$$\begin{bmatrix} r_f \\ \Theta_f \end{bmatrix} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} r_2 \\ \Theta_2 \end{bmatrix} \qquad (25)$$

where

r_f = ray height at fiber plane

Θ_f = ray angle at fiber plane

L = distance from rear of lens to fiber plane

r_2 = ray height at rear surface of GRIN lens

Θ_2 = exit ray angle at rear of GRIN lens

Rays are traced to define the centroid of the spot in the observation plane (front of fibers).

A simple search algorithm is utilized in the fiber model to determine which fibers are illuminated from the point source. It determines the separation of each fiber centroid from the spot centroid and compares that value with the radius of the spot plus fiber radius to ascertain whether or not that fiber is illuminated.

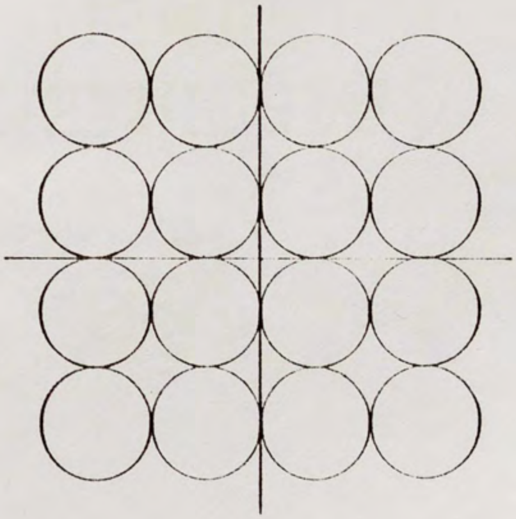

Figure 7. Square Fiber Array Arrangement

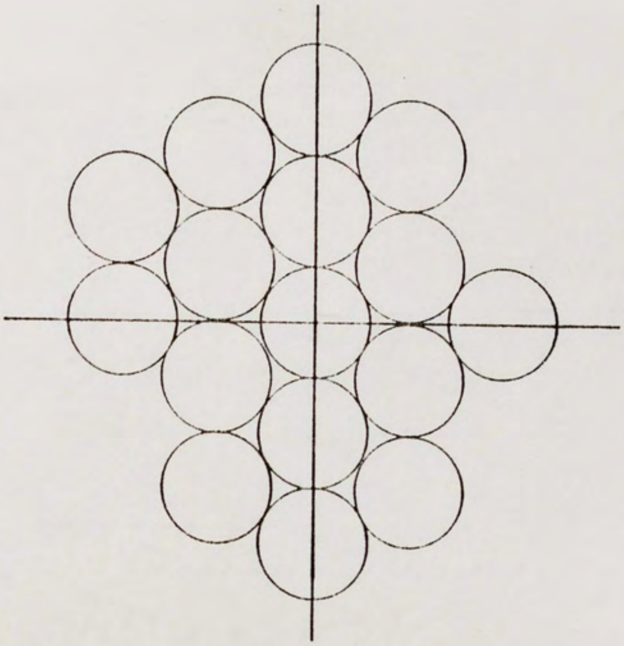

Figure 8. Hexagonal Fiber Array Arrangement

$$\text{Separation of centers} = \sqrt{(x_f - x_s)^2 + (y_f - y_s)^2} \qquad (26)$$

x_f = azimuth coordinate of fiber center

x_s = azimuth coordinate of spot center

y_f = elevation coordinate of fiber center

y_s = elevation coordinate of spot center

If the separation of centers is less than RS+Rf, where RS = radius of spot and Rf = fiber radius, then that fiber is illuminated. This is shown in Figure 9.

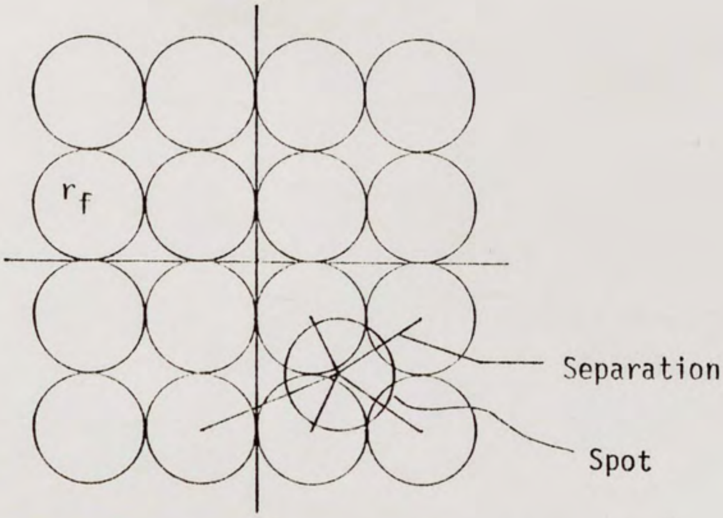

Figure 9. Determination of Illuminated Fibers

An area calculation is then performed to determine the proportion of the spot that falls on each illuminated fiber.

The amount of energy that is coupled into each fiber is also dependent on the fibers numerical aperture (12-14).

> For a step index fiber the NA is defined as follows, refer to Figure 10. The ray shown transversing the fiber strikes the core-cladding interface at the critical angle, Θ_c. Θ is the largest external angle for which a mode will propagate in this fiber. The quantity NoSINΘ is the NA of the fiber. When the medium is air, no=1 and NA = SINΘ or
>
> $$NA = (n_1{}^2 - n_2{}^2)^{1/2} \qquad (27)$$

Since the fiber accepts only rays contained within the cone defined by Θ, an input coupling loss occurs if some fraction of the incident light strikes the fiber at angles greater than Θ. Similarly, if the detector at the output of the fibers cannot receive all angles of light up to θ, power is lost. In this study the detector is not modeled since relative intensity values are used in the detection algorithms, and thus the power emitted at the output of the fibers is the desired quantity to be measured.

To calculate the power transferred into a fiber from the point source (1), the intensity calculated via equation 22 is multiplied by the illuminated area of the front surface of the fiber for rays that have $\theta \leq \theta_{\text{external critical}}$. For rays outside this angle, no modal excitation is assumed. Further improvements in this model would include a scaling of modal excitation due to the diverging lens input rays from the defocused spot.

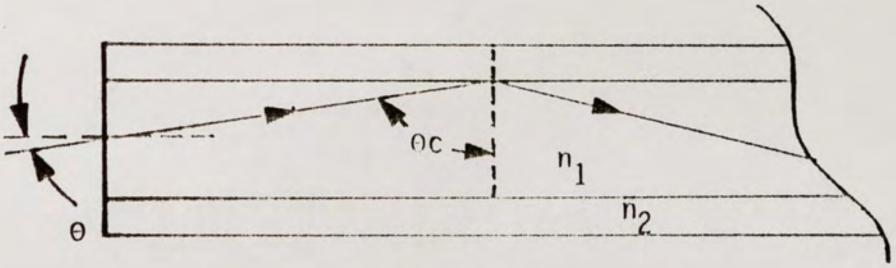

Figure 10. Maximum Entrance Angle Definition of Numerical Aperture For An Optical Fiber

This chapter discussed the power transferred from a point source through an eyelet of a multi-aperture optical system. Physical optics and geometrical optics were combined to develop a flexible model useful in predicting the performance of an eyelet. The implementation of this model in software is listed in Appendix A.

CHAPTER 3

DETECTION ALGORITHMS

One of the purposes of this research was to develop algorithms to determine the absolute position of two point sources located in the field-of-view of the eyelet. This was to be based on input data from either a real eyelet system or the model described in Chapter 3. This permits direct comparisons between simulation and real data. This chapter discusses the development of the detection algorithms.

Traditionally, the Rayleigh criterion has been used as a measure of optical system resolution or resolving power. According to the Rayleigh criterion (15), two images are just resolved when the principal maximum of one coincides with the first minimum of the other. This is shown in Figure 11.

Using this criterion, for a single aperture optical imaging system of focal length, f, and clear aperture diameter of D, two point sources are resolved when separated by a distance r equal to the distance to the first zero of the Airy pattern (J_1 Bessel function), this is

$$r = \lambda(1.22\ f/D) \tag{28}$$

where

$r =$ radius of diffraction spot

$\lambda =$ wavelength

$f =$ focal length

$D =$ aperture diameter

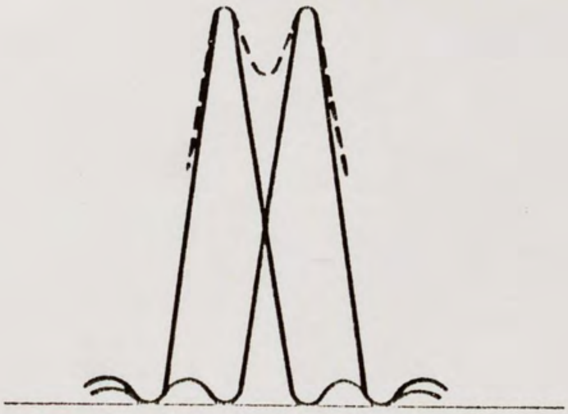

Figure 11. Image Intensity of Two Points Separated By The Rayleigh Criterion

From equation 28, one can see that as the aperture diameter increases the minimum resolvable distance between the two point sources decreases. Two objects can be brought closer together and still be resolved.

But, unless the detector size approaches the Airy disc size, detector size is the limiting factor for resolution. Two objects whose images fall on the same detector cannot be resolved.

An object's position will not be resolved to a new location until it moves from one detector to another. An object which moves within the field-of-view of a detector can not be further resolved by that detector within its field-of-view.

Due to this fact, the fibers in the eyelet system are moved out of the focal plane to a position where at least three fibers are illuminated by a single point. This allows the equivalent pixel to be smaller than the images of the point source. Therefore, the fibers (detector) are not the limiting factor for resolution. The resolution is now limited by the accuracy of the algorithms developed utilizing the output from the three illuminated fibers.

Single-Point Detection Algorithm

The single-point detection algorithm, "LASER3", modified in this research for 2 point detection, is a scaling model using the three highest intensity values from a fiber array. This algorithm and its associated hardware were developed by Dr. Roy Walters at the University of Central Florida. The software listing is given in Appendix C.

The algorithm first sorts the fibers based on intensity; the three largest intensity values are used to determine the position of the spot centroid. The algorithm determines a line both in azimuth and elevation which is based on the separations of the centroids of the three fibers. Once the line is determined, for example in elevation, the relative normalized intensities of the fibers, are used as scaling factors to determine the position of the centroid along the elevation line. This is illustrated in Figure 12.

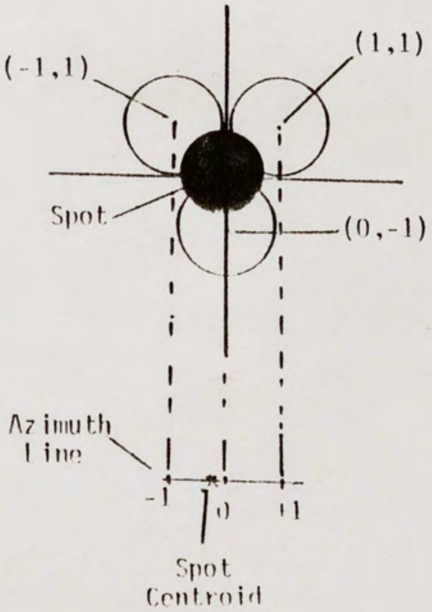

Figure 12. Determination of Single Point Location

The equations used to determine the azimuth and elevation of the point source are:

$$\Delta A = \Theta ELI - \Theta EL0 \qquad (29)$$

$$\Delta B = \Theta EL0 - \Theta EL2$$

$$\Delta ZA = \Theta AZ1 - \Theta AZ0$$

$$\Delta ZB = \Theta AZ2 - \Theta AZ0$$

where

$\Theta EL0$ = elevation position of highest intensity fiber

$\Theta EL1$ = elevation position of second highest intensity fiber

$\Theta EL2$ = elevation position of third highest intensity fiber

$\Theta AZ0$ = azimuth position of highest intensity fiber

$\Theta AZ1$ = azimuth position of second highest intensity fiber

$\Theta AZ2$ = azimuth position of third highest intensity fiber

Linear mode excitation scale factors (first approximation) are given by:

$$F1 = I1/2 \qquad (30)$$
$$F2 = I2/2$$

where

$F1$ = first scale factor

$F2$ = second scale factor

$I1$ = normalized intensity of second highest intensity fiber

$I2$ = normalized intensity of third highest intensity fiber

Equations 29 and 30 are then combined to determine the centroid of the spot.

$$\Theta EL = [(\Theta EL0+F1\Delta A)+(\Theta EL0+F2\Delta B)]/2 \qquad (31)$$
$$\Theta AZ = [(\Theta AZ0+F1\,\Delta\, ZA)+(\Theta AZ0+F2\Delta ZB)]/2$$

where

ΘEL = elevation position of source

ΘAZ = azimuth position of source

In the case of a single point the position can be resolved better than the fiber field-of-view. A position change in the source will cause an intensity change in the three illuminated fibers resulting in a new scale factor and a new object position location prediction.

Two-Point Detection Algorithm

The two-point detection algorithm developed in this research is in three logical parts. TDA assumes that one of the following three conditions could exist.

1) a single point (or two unresolvable points) is present,
2) two well resolved points are present
3) two close but resolvable points are present (the marginal case)

If three fibers are considered as a "single detector," i.e., when a single point source is in the field-of-view of the system three fibers are illuminated, the second point must be separated a defined resolved distance from the first point in order to cause a fourth fiber to be illuminated. The intensity of the spot in the fiber plane is not the airy pattern and therefore the Rayleigh criterion cannot be invoked.

If only three fibers are illuminated, (condition #1) the single-point detection algorithm is used to determine the location of the point source.

If six or more fibers are illuminated then condition 2 exists and two well resolved points are present. The algorithm uses the six fibers with the highest intensity values. It sorts the fibers according to position in the image plane. The fiber optic object space centroid positions are known in azimuth and elevation. These values are converted to image space coordinates by the following expression derived from equation 10.

$$X = \frac{\Theta AZF}{No\sqrt{A}} \qquad (32)$$

$$Y = \frac{\Theta ELF}{No\sqrt{A}}$$

where

X,Y = image plane coordinates in mm

ΘAZF = azimuth angle of fiber in object space (radians)

ΘELF = elevation angle of fiber in object space (radians)

No = on-axis index of refraction of GRIN lens

A = quadratic gradient constant (mm^{-1})

The separation between illuminated fibers is calculated by:

$$S = [(X_1-X_2)^2+(Y_1-Y_2)^2]^{1/2} \qquad (33)$$

where

S = separation between fiber 1 and fiber 2

X_1, Y_1 = centroid of fiber 1

X_2, Y_2 = centroid of fiber 2

The separation between all six fibers is calculated and the two fibers that are farthest apart are then separated into two groups. The remaining four fibers are then compared to the two separated fibers, fiber 1 and fiber 2. The fibers closest to fiber 1 are placed in group 1 and the fibers closest to fiber 2 are placed in group 2. The single-point detection algorithm is first used on group 1, then on group 2 to determine the location of the two points.

If five fibers are illuminated, the same logic is utilized. The two fibers farthest apart are found and separated into two groups, the remaining three fibers are then placed into group 1 and 2 depending on the centroid locations. One fiber will be shared by both groups introducing a slight inaccuracy.

When four fibers are illuminated, condition (3) exists and two close but resolvable points exist. The four illuminated fibers are sorted according to intensity. The separation between the fibers is calculated using equation 33 and the two fibers with the greatest separation are placed into two separate groups. The remaining two fibers are placed in both groups. Thus, two fibers are shared by the two groups for object point location. The single-point detection algorithm is then applied to the two groups to determine the point source locations. This again introduces a small amount of error. The software listing for the two-point detection algorithms in Appendix D.

This chapter discussed the criterion for single-point and two-point detection. The algorithms developed can be utilized with either the actual hardware or the model based computer simulation.

CHAPTER 4

EXPERIMENTAL PROCEDURES AND RESULTS

This chapter explains the experimental procedures and methods used to validate the eyelet model and the two-point detection algorithms.

Experimental Setup

The eyelet system consists of a quarter pitch, SLW series, three millimeter diameter, NSG America SELFOC MICRO lens, on 16 step-index multimode optical fibers. The eyelet system is shown in Figure 13. The important parameters for those components are listed in Table 1.

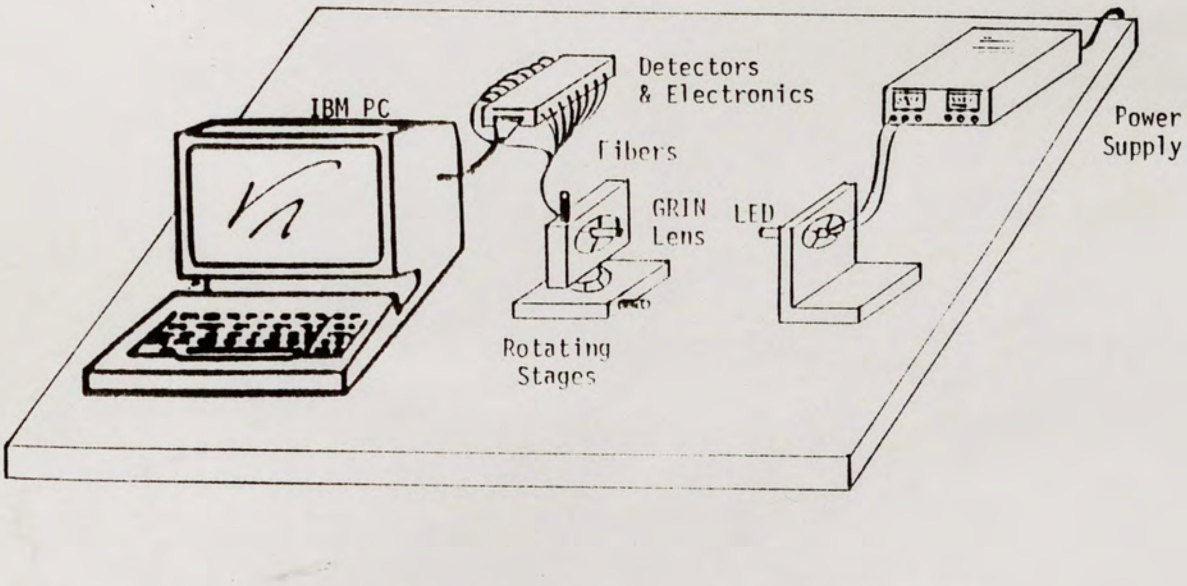

Figure 13. Experimental Hardware Setup

TABLE 1.

EXPERIMENTAL HARDWARE PARAMETERS

GRIN Lens	3 mm	diameter
	0.25	pitch
	1.6075	No
	0.206	A
	0.46	NA
Fiber	0.4mm	core diameter
	0.37	NA
Point Source	0.6 μm	wavelength

An LED was used as a point source in the experimental system.

The experimental configuration was assembled to allow variation of azimuth and elevation of the point source and location of the fibers with respect to the focal plane of the GRIN lens. To achieve angular offset of the point source, the GRIN lens and fiber assembly were mounted on a two-axis rotational stage. The point source remains stationary while the rotational stages provide angular point source offset variation in both azimuth and elevation.

Experimental Results

Utilizing the experimental configuration described above, various measurements were made to verify the detection algorithms. The detection algorithms were also exercised with eyelet model simulation data.

Various azimuth and elevation angles were used to verify the single-point detection algorithm. The measured data and the single-point location prediction are listed in Table 2. The mean error is 1.2 degrees. The eyelet simulation was then exercised using the component characteristic values listed in Table 1. The azimuth and elevation

TABLE 2

SINGLE POINT LOCATION DATA

	MEASUREMENT AND ERROR (DEGREES)	
AZ = 10 DEGREES ELEVATION =	LASER3	ERROR (ABSOLUTE)
-2	-0.6	1.4
-1	-3.2	2.2
0	-0.2	0.2
1	0.0	1.0
2	0.5	1.5
3	3.9	0.9
4	4.3	0.3
5	5.0	0.0
6	7.9	1.9
7	8.7	1.7
8	9.0	1.0
9	9.3	0.3
10	9.5	0.5
11	10.0	1.0
EL = 5 DEGREES AZIMUTH		
3	1.6	1.4
4	2.1	1.9
5	4.1	0.9
6	4.6	1.4
7	5.2	1.8
8	6.3	1.7
9	10.4	1.4
10	11.0	1.0
11	11.7	0.7
12	12.0	0.0
13	12.0	1.0
14	12.6	1.4
15	13.0	2.0
16	12.9	3.1
17	15.8	2.1
18	17.0	1.0
	MEAN ERROR	1.2

angles of Table 2 were used for input with detection algorithm results listed in Table 3. (Using the two-point detection algorithm, TDA, with a single point target i.e., case #1.)

The mean error of the eyelet model input was 0.71 degrees. The mean error between eyelet model inputs and measured data inputs into TDA was 0.88 degrees. It should be noted that the two-point detection algorithm contains LASER3 as the method to locate the point source. For single points, TDA and LASER3 predict the same object coordinates.

A second point source was placed in the field-of-view of the eyelet and the coordinates were determined utilizing the single-point detection algorithm contained in TDA. With both diodes at various azimuth and elevation positions, the two-point detection algorithm was exercised. The results are listed in Table 4. The TDA had the capability to resolve two-points located within 3.1 degrees. Table 5 lists the eyelet model predictions for the same coordinates. Table 6 provides an eyelet model to measured comparison.

The model predicted that two-point sources located at (20.0, 5.0) and (22.2, 3.4) respectively could be resolved, a 2.7 degree resolution capability. The actual hardware could not resolve the two sources located at (20.0, 5.0) and (22.2, 3.4). The model also predicted that two points located at (20.0, 5.0) and (22.2, 3.5) could not be resolved. The eyelet model and actual measured 2 point resolution differed by 0.4 degrees.

TABLE 3

SINGLE POINT LOCATION EYELET MODEL TO MEASURED COMPARISON

MEASUREMENTS AND ERROR (DEGREES)

AZ = 10 DEGREES ELEVATION =	LASER3 ACTUAL DATA	TDA MODEL DATA	ERROR (ABSOLUTE)	
			MEASURED	MODEL
-2	-0.6	-1.2	1.4	0.8
-1	-3.2	-0.3	2.2	0.7
0	-0.2	-0.3	0.2	0.3
1	0.0	0.4	1.0	0.6
2	0.5	1.0	1.5	1.0
3	3.9	2.8	0.9	0.2
4	4.3	3.7	0.3	0.3
5	5.0	4.6	1.0	0.4
6	7.9	5.8	1.9	0.2
7	8.7	8.1	1.7	1.1
8	9.0	8.6	1.0	0.6
9	9.3	10.0	0.3	1.0
10	9.5	10.1	0.5	0.1
11	10.0	10.2	1.0	0.8
EL = 5 DEGREES AZIMUTH =				
3	1.6	2.4	1.4	0.6
4	2.1	3.9	1.9	0.1
5	4.1	4.2	0.9	0.8
6	4.6	4.5	1.4	1.5
7	5.2	6.2	1.8	0.8
8	6.3	6.9	1.7	1.1
9	10.4	10.1	1.4	1.1
10	11.0	10.9	1.0	0.9
11	11.7	11.5	0.7	0.5
12	12.0	11.5	0.0	0.5
13	12.0	11.8	1.0	1.2
14	12.6	12.7	1.4	1.3
15	13.0	16.2	2.0	1.2
16	12.9	16.9	3.1	0.9
17	15.8	17.4	1.2	0.4
18	17.0	17.6	1.0	0.4
	MEAN ERROR		1.2	0.71

TABLE 4

TWO-POINT RESOLUTION MEASUREMENTS

MEASUREMENTS AND ERROR (DEGREES)

PRIMARY DIODE		SECONDARY DIODE		TDA PRIMARY		TDA SECONDARY		ERROR PRIMARY		ERROR SECONDARY		SEPARATION ANGLE
AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	
10.0	5.0	12.4	3.0	14.8	3.1	18.7	1.3	-4.8	2.0	-6.3	1.7	3.1
10.0	5.0	15.7	-3.9	15.0	5.8	11.4	-4.4	-1.7	-0.8	4.3	0.5	10.6
10.0	5.0	20.5	5.5	15.0	3.0	18.4	1.7	-5.0	-0.5	2.1	3.8	10.5
20.5	5.0	18.8	-6.6	20.6	5.3	19.5	-6.8	-0.6	-0.3	-0.7	0.2	11.6
20.0	5.0	15.9	-5.3	20.6	5.3	15.2	-5.1	0.6	-0.3	0.7	-0.2	11.1
20.0	5.0	22.2	2.4	20.6	5.3	22.3	2.8	-0.6	-0.3	-0.1	-0.4	3.4
20.0	5.0	22.2	3.4	----------------COULD NOT RESOLVE----------------								(2.7)
20.0	5.0	16.0	-5.4	20.6	5.3	15.2	-5.1	-0.6	-0.3	0.8	-0.3	11.1
20.0	5.0	14.2	-2.9	20.5	5.2	15.0	-2.2	-0.5	-0.2	-0.8	-0.7	9.8
20.0	5.0	21.0	-3.6	20.5	5.3	21.8	1.7	-0.5	-0.3	-0.8	5.3	8.7
												MINIMUM RESOLUTION ANGLE
						MEAN ERROR		1.7	.6	1.8	1.5	3.1

TABLE 5

TWO-POINT RESOLUTION EYELET MODEL PREDICTIONS

MODEL AND ERROR (DEGREES)

PRIMARY DIODE		SECONDARY DIODE		TDA PRIMARY		TDA SECONDARY		ERROR PRIMARY		ERROR SECONDARY		SEPARATION
AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	ANGLE
10.0	5.0	12.4	3.0	10.9	4.5	14.5	6.1	0.9	0.5	2.1	3.1	3.1
10.0	5.0	15.7	-3.9	11.7	2.4	14.2	-3.8	1.7	2.6	1.5	0.1	10.6
10.0	5.0	20.5	5.5	12.8	4.4	19.3	4.8	2.8	0.6	1.2	0.7	10.5
20.0	5.0	18.8	-6.6	20.2	4.9	20.4	-6.5	0.2	0.1	1.6	0.1	11.6
20.0	5.0	15.9	-5.3	19.3	4.5	16.2	-3.2	0.7	0.5	0.3	2.1	11.1
20.0	5.0	22.2	2.4	19.9	5.0	21.3	3.0	0.1	0.0	0.9	0.6	3.4
20.0	5.0	22.2	3.4	19.8	4.9	21.5	3.0	0.2	0.1	0.7	0.4	2.7
20.0	5.0	16.0	-5.4	19.0	2.6	14.9	-2.6	1.0	2.4	1.1	2.8	11.1
20.0	5.0	14.2	-2.9	17.8	1.6	16.4	-1.0	2.2	3.4	2.2	1.9	9.8
20.0	5.0	21.0	-3.6	19.8	2.3	21.9	-3.5	0.2	2.7	0.9	0.1	8.7
												MINIMUM RESOLUTION ANGLE
							MEAN ERROR	1.0	1.5	1.3	1.2	2.7

TABLE 6

TWO-POINT EYELET MODEL AND MEASURED COMPARISON

MEASURED								MODEL				MODEL VS. MEASURED			
PRIMARY DIODE		SECONDARY DIODE		TDA PRIMARY		TDA SECONDARY		TDA PRIMARY		TDA SECONDARY		ERROR PRIMARY		ERROR SECONDARY	
Az	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL	AZ	EL
10.0	5.0	12.4	3.0	14.8	3.1	18.7	1.3	10.9	4.5	14.5	6.1	3.9	1.4	4.2	4.8
10.0	5.0	15.7	-3.9	11.7	5.8	11.4	-4.4	11.7	2.4	14.2	-3.8	0	3.4	2.8	0.6
10.0	5.0	20.5	5.5	15.0	3.0	18.4	3.0	12.8	4.4	19.3	4.8	2.2	1.4	0.9	3.1
20.0	5.0	18.8	-6.6	20.6	5.3	19.5	-6.8	20.2	4.9	20.4	-6.5	0.4	0.4	0.9	0.3
20.0	5.0	15.9	-5.3	20.6	5.3	15.2	-5.1	19.3	4.5	16.2	-3.2	1.3	0.8	1.0	1.9
20.0	5.0	22.2	2.4	--COULD NOT RESOLVE---				19.8	4.9	21.5	3.0	*	*	*	*
20.0	5.0	16.0	-5.4	20.6	5.3	15.2	-5.1	19.0	2.6	14.9	-2.6	1.6	2.7	0.3	2.5
20.0	5.0	14.2	-2.9	20.5	5.2	15.0	-2.2	17.8	1.6	16.4	-1.0	2.7	3.6	1.4	1.2
20.0	5.0	21.0	-3.6	20.5	5.3	21.8	1.7	19.8	2.3	21.9	-3.5	0.7	3.0	0.1	5.2
										MEAN ERROR		1.5	1.9	1.4	2.2

*Model values resolved these two points
Model predicted two points located at (20.0, 5.0) and (22.2, 3.5)
Could not be resolved

The major causes of error in the experimental results can be attributed to:

1. Inaccurate centroid measurement.
2. Nonsymmetrical modal excitation in fibers.
3. Use of a linear excitation form factor.

When the experimental hardware is used, the object space coordinates of each fiber must be determined. To determine the object space centroid in azimuth and elevation the position of the source is changed with respect to the GRIN lens. The location that produces the highest intensity output for a fiber is used as the object space centroid location for that fiber. Inaccuracies in this measurement account for the majority of errors in the experimental results.

The intensity scale factors that are used in LASER3 assume uniform modal excitation in the fibers and does not account for the variation with angle that exists.

A cause of error in the eyelet model is the arbitrary angular extinction of propagation in the fiber. The fiber model assumes all rays with an angle less than the external critical angle propagate thru the fiber and does not take into account the losses due to the incidence angle.

This chapter discussed the experimental setup that was used to validate the computer simulation model and verify the detection algorithms. The detection algorithms were exercised with experimental data and simulation data, the results were compared to validate the computer eyelet model. The mean error of detection was 1.4 degrees overall for the eyelet model. The detection algorithm locations were compared to actual measured locations and the mean error was 1.2 degrees. The resolution of the hardware system was 3.1 degrees and that of the eyelet model 2.7 degrees.

CONCLUSIONS

The purpose of this research was to develop a two-point detection algorithm for an eyelet of a multi-aperture optical system. The algorithm was based on allowing three fibers to be illuminated by a single-point source. A computer simulation model of a multi-aperture eyelet was developed and validated with experimental data producing an overall mean error of 1.4 degrees.

The eyelet model was used to develop a two-point detection algorithm. The two-point detection algorithm provided a 3.1 degree resolution capability. If the system had been focused the resolution would have been limited by the size of the fiber and the system resolution point detection algorithm gives a resolution improvement of 40 percent.

The computer eyelet model is composed of three sub-models, a source model, GRIN lens model, and a fiber model. The model combines geometrical and physical optics to predict the output of the eyelet under various conditions. Ray matrices are used to propagate the rays from the point source to the fiber plane and determine the size and position of the spot at the fiber plane. Radiometric principles are applied to the point source to determine the power collected by the GRIN lens. A diffraction integral is utilized to calculate the intensity of the spot at the fiber plane. The fiber plane may be located either at the focal plane of the GRIN lens or removed from the focal plane. The fiber egergy transfer model is a simple area calculation to determine the amount of power coupled into the fiber. The eyelet model is a flexible model giving multi-aperture researches a valuable tool in developing various algorithms. The results between model and measured values compared favorably.

There are many areas of research in multi-aperture optical systems that could utilize the results of this research. The eyelet model developed could be modified to predict the performance of many eyelets instead of a single eyelet. The detection algorithms could be exercised with 32 inputs instead of 16 to provide a larger field-of-view system. This research demonstrated the ability of an inexpensive, easily assembled system to resolve two-points within 3.1 degrees. Further research can provide a simple, low cost system that could resolve and track targets.

APPENDIX A

POWER CALCULATION

Figure 14 shows the geometry of a collection aperture and emitting source. The power collected by an optical system with a circular aperture of radius, r, is given by (7):

$$P = EA_p \tag{34}$$

where

P = Power in watts

E = Irradiance of the source (w/cm^2)

A_p = Projected area (cm^2)

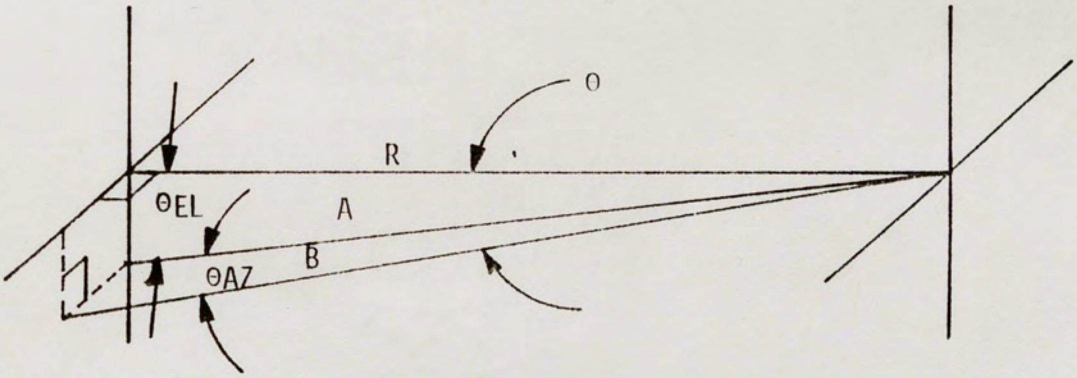

Figure 14. Geometry of Point Source and Collecting Aperture

The projected area is given by the area of the aperture projected through the angle between the normal to the aperture and the line of sight.

$$A_p = A\cos\Theta \qquad (35)$$

$A = \pi r^2$

Θ = Angle between normal and line of sight

This projected area can also be expressed in terms of the elevation and azimuth angles. Referring to Figure 14 for nomenclature, $\cos\Theta$ is given by

$$\cos\Theta = \frac{R}{B} \qquad (36)$$

$$\cos\Theta_{AZ} = \frac{A}{B} \qquad (37)$$

$$\cos\Theta_{EL} = \frac{R}{A} \qquad (38)$$

rearranging equations 37 & 38:

$$B = A/\cos\Theta_{AZ} \qquad (39)$$

$$R = A\cos\Theta_{EL}$$

substituting 39 into 36

$$\cos\Theta = \frac{A\cos\Theta_{EL}}{A/\cos\Theta_{AZ}}$$

or

$$\cos\Theta = \cos\Theta_{EL}\cos\Theta_{AZ} \qquad (40)$$

So equation 34 becomes

$$P = EA\cos\Theta_{AZ}\cos\Theta_{EL}$$

APPENDIX B

SOFTWARE LISTING FOR THE EYELET MODEL

```
10 REM ***************************************************************
20 REM ************************PROGRAM HEX******************************
30 REM MAOSIM (MULTIAPERTURE OPTICAL SYSTEM INTENSITY MODEL)
40 REM STEVE MARLOW JANUARY 20,1987 REVISED APRIL 29,1987
50 REM THIS PROGRAM CALCULATES THE INTENSITY FOR A SINGLE APERTURE
60 REM OF A MULTIAPERTURE OPTICAL SYSTEM.
70 REM A SOURCE WITH INPUT POWER (WATTS) IS PROPAGATED FROM THE SOURCE
80 REM TO A GRADIENT-INDEX LENS (PLANO-CONVEX OR FLAT) AND FROM THE
90 REM BACK OF THE LENS TO THE FIBER BUNDLE (THE FIBERS CAN BE PLACED
100 REM AT ANY POINT BEHIND THE LENS) AND THE POWER IS COUPLED INTO
110 REM THE FIBERS AND PROPAGATED TO THE OUTPUT PLANE OF THE FIBERS.
120 REM *****************************************************************
130 REM ************************VARIABLES********************************
140 REM LENS INPUT PARAMETERS :
150 REM A=QUADRATIC GRADIENT CONSTANT (1/MM)
160 REM N=REFRACTIVE INDEX ON AXIS
170 REM RD=RADIUS OF CURVATURE OF CONVEX SURFACE (mm)
180 REM P=LENS PITCH
190 REM PHI=LENS DIAMETER (mm)
200 REM FIBER INPUT PARAMETERS :
210 REM FPHI=FIBER DIAMETER (mm)
220 REM NA=NUMERICAL APERTURE
230 REM SOURCE INPUT PARAMETERS :
240 REM WL=WAVELENGTH IN MICRONS
250 REM PS=SOURCE POWER IN WATTS
260 REM TS=SOURCE DIVERGENCE ANGLE (DEGREES)
270 REM TDL=SORCE DIVERGING LENS TRANSMISSION
280 REM AZ=AZIMUTH ANGLE
290 REM EL=ELEVATION ANGLE
300 REM GEOMETRICAL INPUT PARAMETERS:
310 REM L=DISTANCE FIBERS ARE FROM BACK OF LENS (MM)
320 REM SD=SOURCE TO LENS DISTANCE (mm)
330 REM THE PROGRAM CALCULATES THE FOLLOWING VALUES:
340 REM S=DISTANCE FROM BACK OF LENS TO FOCAL POINT (MM)
350 REM EFL= FOCAL LENGTH (MM)
360 REM COORDINATES
370 REM LENS COORDINATES:
380 REM HIX(I)= ARRAY OF ENTRANCE RAY HEIGHTS (mm) IN THE X-PLANE
390 REM HIY(I)= ARRAY OF ENTRANCE RAY HEIGHTS (mm) IN THE Y-PLANE
400 REM OIx(I)=ARRAY OF EXIT RAY HEIGHTS FROM LENS (mm) IN THE X-PLANE
410 REM OIY(I)=ARRAY OF EXIT RAY HEIGHTS FROM LENS (mm) IN THE Y-PLANE
420 REM EIA(I)=ARRAY OF EXIT RAY ANGLES FROM LENS AZIMUTH
430 REM EIE(I)=ARRAY OF EXIT RAY ANGLES FROM LENS ELEVATION
440 REM FIBER PLANE COORDINATES :
450 REM HFx(I)=ARRAY OF RAY HEIGHTS AT FIBER (mm) IN THE X-PLANE
460 REM HFY(I)=ARRAY OF RAY HEIGHTS AT FIBER (mm) IN THE Y-PLANE
470 REM FC(I,1)= THE X COORDINATE OF THE CENTROID OF THE I(th) FIBER
480 REM FC(I,2)= THE Y COORDINATE OF THE CENTROID OF THE I(th) FIBER
490 REM AREA(I)= THE AMOUNT OF ILLUMINATED AREA OF THE I(TH) FIBER
500 REM SEP(I)= THE SEPERATION BETWEEN THE CENTROID OF THE SPOT
510 REM         AND THE CENTROID OF THE I(th) FIBER
520 REM PIX(I)=IF PIx IS 1 THEN FIBER IS ILLUMINATED IF PIX IS O
530 REM           THEN FIBER HAS NO ILLUMINATION.
540 REM PIXL(I)= IS THE LENGTH OF OVERLAP OF THE SPOT ON THE I(TH) FIBER
550 REM INTENSITY PARAMETERS :
560 REM IGL=INTENSITY FROM POINT SOURCE INCIDENT AT GRIN LENS (WATTS)
570 REM IFP(r)=INTENSITY AT THE FIBER PLANE
580 REM PF(I)=ARRAY OF POWER LEAVING FIBERS
590 REM THE INTENSITY AT THE FIBER PLANE IS CALCULATED BY UU*
600 REM WHERE U IS GIVEN BY THE DIFFRACTION INTEGRAL
610 REM CI= COS PORTION OF THE DIFFRACTION INTEGRAL
620 REM SINT=SIN PORTION OF THE DIFFRACTION INTEGRAL
630 REM *****************************************************************
640 REM *****************DIMENSION STATEMENTS****************************
650 DIM EIA(10),OIY(10),HFY(10),HIY(10),PF(20),IFP(20)
660 DIM EIE(10),OIx(10),HFx(10),HIx(10),IFLAG(20)
670 DIM XPRIME(20),YPRIME(20),RHO(20),SINT(20),CI(20)
680 DIM FC(16,2),AREA(16),SEP(16),PIX(16),PIXL(16),PIXV(16)
690 DIM L(25),KF(25),PQ(25),AZ(16),AZR(16),EL(16),ELR(16)
700 DEFINT D
710 REM ********************************************************************
720 REM ***************************INPUTS***********************************
730 REM THIS PORTION OF THE PROGRAM COLLECTS THE BASIC PARAMETERS
740 REM NEEDED TO PERFORM THE CALCULATIONS.
750 INPUT "WHAT IS QUADRATIC GRADIENT CONSTANT (1/mm)? ",A
760 INPUT "WHAT IS REFRACTIVE INDEX ON AXIS? ",N
770 INPUT "WHAT IS RADIUS OF CURVATURE OF CONVEX SURFACE (MM)? ",RD
780 INPUT "WHAT IS LENS PITCH (P)? ",P
790 INPUT "WHAT IS NUMERICAL APERTURE OF LENS? ",NAL
800 INPUT "WHAT IS BACK OF LENS TO FIBER DISTANCE (mm)? ",L
810 INPUT "WHAT IS NUMERICAL APERTURE (NA) OF FIBER? ",NA
820 INPUT "WHAT IS FIBER DIAMETER (mm)? ",FPHI
830 INPUT "WHAT IS SOURCE POWER (WATTS)? ",PS
840 INPUT "WHAT IS SOURCE WAVELENGTH (microns) ? ",WLM
850 INPUT "WHAT IS DIVERGENCE ANGLE OF SOURCE (DEGREES)? ",TS
860 INPUT "WHAT IS AZIMUTH ANGLE (DEGREES)? ",AZ
870 INPUT "WHAT IS ELEVATION ANGLE (DEGREES)? ",EL
880 INPUT "WHAT IS TRANSMISSION OF SOURCE DIVERGING LENS? ",TDL
```

```
890 INPUT "WHAT IS SOURCE 10 LENS DISTANCE (mm)? ",SD
900 INPUT "WHAT IS DIAMETER OF LENS (mm)? ",PHI
910 INPUT "DEFAULT ARRAY (ENTER 0) OR INPUT ARRAY (ENTER 1) ?",ARFL
920 IF ARFL=1 THEN GOTO 1290
930 REM ******************END OF USER INPUTS******************************
940 REM *********************************************************************
950 REM ******************DEFINE FIBER POSITIONS*****************************
960 FC(1,1)= 0
970 FC(1,2)= 0
980 FC(2,1)= .707*FPHI
990 FC(2,2)=(1/2)*FPHI
1000 FC(3,1)=.707*FPHI
1010 FC(3,2)=-(1/2)*FPHI
1020 FC(4,1)=0
1030 FC(4,2)=-FPHI
1040 FC(5,1)=-.707*FPHI
1050 FC(5,2)=-(1/2)*FPHI
1060 FC(6,1)=-.707*FPHI
1070 FC(6,2)=(1/2)*FPHI
1080 FC(7,1)=0
1090 FC(7,2)=FPHI
1100 FC(8,1)=.707*FPHI
1110 FC(8,2)=(3/2)*FPHI
1120 FC(9,1)=2*FPHI
1130 FC(9,2)=0
1140 FC(10,1)=2*FPHI
1150 FC(10,2)=-FPHI
1160 FC(11,1)=.707*FPHI
1170 FC(11,2)=-(3/2)*FPHI
1180 FC(12,1)=0
1190 FC(12,2)=-2*FPHI
1200 FC(13,1)=-.707*FPHI
1210 FC(13,2)=-(3/2)*FPHI
1220 FC(14,1)=-2*FPHI
1230 FC(14,2)=0
1240 FC(15,1)=-.707*FPHI
1250 FC(15,2)=(3/2)*FPHI
1260 FC(16,1)=0
1270 FC(16,2)=2*FPHI
1280 GOTO 1410
1290 FOR I=1 TO 16
1300 PRINT "WHAT IS AZIMUTH FOR FIBER # I",I
1310 INPUT "ENTER VALUE IN DEGREES",AZ(I)
1320 PRINT "WHAT IS ELEVATION FOR FIBER # I",I
1330 INPUT "ENTER VALUE IN DEGREES",EL(I)
1340 NEXT I
1350 FOR I=1 TO 16
1360 AZR(I)=AZ(I)*3.141593/180
1370 ELR(I)=EL(I)*3.141593/180
1380 FC(I,1)=AZR(I)/(N*A)
1390 FC(I,2)=ELR(I)/(N*A)
1400 NEXT I
1410 REM *********************************************************************
1420 REM CALCULATIONS FOR VARIABLES TO BE USED IN THE RAY MATRIX EQUATIONS
1430 PI=3.141593
1440 B=PI*2*P
1450 X=COS(B)
1460 Y=SIN(B)
1470 IF RD=0 THEN Q=0 ELSE Q=(N-1)/RD
1480 TSRAD=TS*PI/180
1490 AZR=AZ*PI/180
1500 ELR=EL*PI/180
1510 REM *********************************************************************
1520 REM GEOMETRIC CALCULATIONS (EFL,S,WL CONVERSION TO mm)
1530 EFL=1/(N*A*Y)
1540 ZL=EFL+L
1550 WL=WLM*.001
1560 S=(X-(Q*Y)/(N*A))/((Q*X)+(N*A*Y))
1570 NALR=ATN(NAL/((1-NAL↑2)↑.5))
1580 NAR=ATN(NA/((1-NA↑2)↑.5))
1590 IF AZR>NALR THEN :PRINT "AZ IS TO LARGE" :STOP
1600 IF ELR>NALR THEN :PRINT "EL IS TO LARGE" :STOP
1610 REM *********************************************************************
1620 REM *******************RAY MATRIX CALCULATIONS****************************
1630 FOR I=0 TO 10
1640 HIY(I)=(-PHI/2)+(I*PHI/10)
1650 HIX(I)=(-PHI/2)+(I*PHI/10)
1660 OIX(I)=(HIX(I)*X)-((HIX(I)*Q)/(N*A))*Y+(AZR*Y)/(N*A)
1670 OIY(I)=(HIY(I)*X)-((HIY(I)*Q)/(N*A))*Y+(ELR*Y)/(N*A)
1680 EIE(I)=-(HIY(I)*Q*X)-(HIY(I)*N*A*Y)+ELR*X
1690 EIA(I)=-(HIX(I)*Q*X)-(HIX(I)*N*A*Y)+AZR*X
1700 HFX(I)=OIX(I)+EIA(I)*L
1710 HFY(I)=OIY(I)+EIE(I)*L
1720 NEXT I
1730 REM ****************************************************************
1740 REM THIS PART OF THE CODE DETERMINES WHICH PIXELS ARE ILLUMINATED
1750 IF L=0 THEN RS=PI*EFL*NAL↑3/2*N↑2 ELSE RS=ABS(HFX(5)-HFX(0))
1760 RF=FPHI/2
```

```
1770 PRINT "HFY (5) IS ",HFY(5)
1780 PRINT "HFX(5) IS ",HFX(5)
1790 RTEST=RS+RF
1800 FOR I=1 TO 16
1810 SEP(I)=((FC(I,1)-HFX(5))↑2+(FC(I,2)-HFY(5))↑2)↑(1/2)
1820 IF SEP(I)<RTEST THEN PIX(I)=1 ELSE PIX(I)=0
1830 IF PIX(I)=1 THEN :GOSUB 2760
1840 IF AREA(I)>1 THEN PRINT "ERROR AREA IS > 1"
1850 NEXT I
1860 REM ********************INTENSITY CALCULATIONS**************************
1870 IGL=(PS*TDL*COS(AZR)*COS(ELR)*(PHI/2)↑2)/((SD)↑2*(SIN(TSRAD/2))↑2*4)
1880 IF L=0 THEN EPS=0 ELSE EPS=(1/ZL-1/EFL)
1890 FOR JL=1 TO 16
1900 IFP(JL)=0
1910 IF PIX(JL)=0 THEN :GOTO 2170
1920 RHO(JL)=SEP(JL)
1930 IF RHO(JL)=0 THEN RHO(JL)=.001
1940 BETA=2*PI*RHO(JL)/(WLM*ZL)
1950 XD=BETA*PHI/5
1960 SINT(JL)=0
1970 CI(JL)=0
1980 RMAX=BETA*PHI/2
1990 TFIB=ATN(RMAX/ZL)
2000 FOR R=0 TO RMAX STEP XD
2010 ALPHA=PI*EPS*R↑2/(WL*BETA↑2)
2020 W=R
2030 GOSUB 2280
2040 CAL=COS(ALPHA)
2050 SAL=SIN(ALPHA)
2060 IF R=RMAX THEN CL=.5*W*CAL*BJ AND SL=.5*W*SAL*BJ :GOTO 2090
2070 CI(JL)=W*CAL*BJ+CI(JL)
2080 SINT(JL)=W*SAL*BJ+SINT(JL)
2090 NEXT R
2100 CI(JL)=(CI(JL)+CL)*XD
2110 SINT(JL)=(SINT(JL)+SL)*XD
2120 TFAC=(2*PI/(WL*ZL*BETA↑2))↑2*(1/1000)↑2
2130 TF2=(CI(JL))↑2
2140 TF3=(SINT(JL))↑2
2150 IFP(JL)=IGL*TFAC*(TF2+TF3)*EXP(-2*(TFIB/NAR)↑2)
2160 PIXV(JL)=IFP(JL)*AREA(JL)
2170 NEXT JL
2180 FOR I=1 TO 16
2190 PRINT "PIXV IS    ",PIXV(I)
2200 NEXT I
2210 INPUT "RUN AGAIN (YES=1 NO=0) :",RFL
2220 IF RFL=0 THEN GOTO 3020
2230 INPUT "ENTER AZ IN DEGREES ",AZ
2240 INPUT "ENTER EL IN DEGREES ",EL
2250 GOTO 1420
2260 REM***********************************************************************
2270 REM*********** SUBROUTINE BESSEL FUNCTION CALCULATION********************
2280 REM BESSEL FUNCTION ROUTINE
2290 REM THIS ROUTINE USES THE RECURRANCE RELATION TECHNIQUE TO
2300 REM COMPUTE THE BESSEL FUNCTION OF THE FIRST KIND FOR A GIVEN ARGUMENT
2310 REM W AND ORDER 0.
2320 REM INPUT :
2330 REM         W=THE ARGUMENT OF THE BESSEL FUNCTION
2340 REM         0=THE ORDER OF THE BESSEL FUNCTION
2350 REM OUTPUT:
2360 REM         BJ=THE RESULTANT BESSEL FUNCTION
2370 IF W>14 THEN :GOTO 2460
2380 BJ=1
2390 KFAC=1
2400 FOR K=1 TO 20
2410 J=2*K
2420 KFAC=KFAC*K
2430 BJ=BJ+((-1)↑K*(W/2)↑J)/(KFAC↑2)
2440 NEXT K
2450 GOTO 2730
2460 L(1)=11025/(8*W)↑2
2470 P=1-(9/2)*(1/(8*W)↑2)+L(1)/(24*(8*W)↑2)
2480 II=-1
2490 KF(0)=1
2500 FOR I=3 TO 11 STEP 2
2510 M=I-2
2520 L(I)=(L(M)/(8*W)↑2)*(2*I+3)↑2*(2*I+5)↑2
2530 NEXT I
2540 FOR I=1 TO 7
2550 K=2*I-1
2560 KF(I)=(2*I)*K*KF(I-1)
2570 NEXT I
2580 FOR I=2 TO 6
2590 J=I+1
2600 K=2*I-1
2610 P=P+II*L(K)/KF(J)
2620 II=-II
2630 NEXT I
2640 JJ=-1
```

```
2650 PQ(1)=37.5/(8*W)↑3
2660 Q=PQ(1)-(1/(8*W))
2670 FOR K=3 TO 11 STEP 2
2680 PQ(K)=(2*K+1)↑2*(2*K+3)↑2*PQ(K-2)/((8*W)↑2*(K+2)*(K+1))
2690 Q=Q+PQ(K)*JJ
2700 JJ=-JJ
2710 NEXT K
2720 BJ=((P-Q)/(PI*W)↑.5)*SIN(W)+((P+Q)/(PI*W)↑.5)*COS(W)
2730 RETURN
2740 REM ********************END OF BESSEL SUBROUTINE***************************
2750 REM*************************************************************************
2760 REM ********************* AREA SUBROUTINE *********************************
2770 REM SUBROUTINE TO CALCULATE THE AREA OF THE SPOT ON THE FIBER
2780 AREA(I)=0
2790 IF HFX(5)=FC(I,1) AND HFY(5)=FC(I,2) THEN FLAG=1 ELSE FLAG=0
2800 IF RS>RF AND FLAG=1 THEN AREA(I)=1
2810 IF RS=RF AND FLAG=1 THEN AREA(I)=1
2820 RDEL=RS+SEP(I)
2830 IF RS<RF AND RDEL<RF THEN AREA(I)=(RS/RF)↑2
2840 IF RS<RF AND RDEL=RF THEN AREA(I)=(RS/RF)↑2
2850 IF SEP(I)+RF<RS AND RS>RF THEN AREA(I)=1
2860 IF RF+SEP(I)=RS AND RS>RF THEN AREA(I)=1
2870 IF AREA(I)=0 THEN PIXL(I)=RF+RS-SEP(I) ELSE :GOTO 2990
2880 IF RS>RF AND PIXL(I)>RF THEN AREA(I)=PIXL(I)/(2*RF) :GOTO 2990
2890 HL=PIXL(I)/2
2900 XS=(RS-HL)/RS
2910 ACXS=(PI/2)-ATN(XS/((1-XS↑2)↑(.5)))
2920 IF HL>RF THEN AREA(I)=1 :GOTO 2990
2930 XF=(RF-HL)/RF
2940 ACXF=(PI/2)-ATN(XF/((1-XF↑2)↑(.5)))
2950 AR1=RF↑2*ACXF-(RF-HL)*((RF*HL*2-HL↑2))↑(.5)
2960 AR2=RS↑2*ACXS-(RS-HL)*((RS*HL*2-HL↑2))↑(.5)
2970 AREA(I)=(AR1+AR2)/(RF↑2)
2980 IF AREA(I)>1 THEN AREA(I)=PIXL(I)/(2*RF)
2990 RETURN
3000 REM ****************** END OF AREA SUBROUTINE ****************************
3010 REM ***********************************************************************
3020 END
```

APPENDIX C

SOFTWARE LISTING FOR SINGLE-POINT DETECTION

```
10 '*******************************************************************************
20 '*     SIXTEEN CHANNEL INPUT MULTIAPERTURE ARRAY LASER SENSOR                  *
30 '*                  by R. Walters                 Rev. 1.01  12-20-86          *
40 '*******************************************************************************
50 '
60 CLS
70 CLEAR, 49152!
80 SCREEN 0,0,0:KEY OFF
90 DEF SEG = 0
100 ,200L
110 DIM TR(15)
120 SG = 256 * PEEK(&H511) + PEEK(&H510)
130 SG = SG + 49152!/16
140 DEF SEG = SG
150 BLOAD "DASH16.BIN", 0
160 DIM DIO%(8)
170 DIM P(16)
180 DIO%(0)=768 : DIO%(1) = 2 : DIO%(2) = 3
190 DASH = 0
200 PRINT "                           MULTIAPERTURE LASER SENSOR":PRINT
210 PRINT "        by Roy A. Walters, Ph.D.,                    (UCF, Orlando, Fl.)"
220 PRINT
230 FLAG% = 0
240 MD% = 0
250 CALL DASH16 (MD%, DIO%(0),FLAG%)
260 '
270 'Set channel scan limits
280 MD%=1
290 DIO%(0)=0
300 DIO%(1)=15
310 FOR N=2 TO 4:DIO%(N)=0:NEXT N
320 FLAG%=X
330 CALL DASH16 (MD%, DIO%(0), FLAG%)
340 FOR N= 0 TO 4
350 DIO%(N)=0
360 NEXT N
370 FLAG%=0
380 PRINT"This program gives the azimuth and elevation of a laser source  Data is "
390 PRINT "based on COORDINATE inputs to the CALIB program.
400 PRINT "Use only STEADY STATE light sources.          "
410 PRINT
420 PRINT "                 ************************************"
430 PRINT "                 *         PERFORM NORMALIZATION    *"
440 PRINT "                 ************************************":PRINT
450 PRINT "If you have not changed fiber optic connections, this step is not necessary"
460 CLS
470 DIM AR(16)
480 IF NORM$ = "N" OR NORM$="n" THEN GOTO 850
490 PRINT: PRINT "Place diffusion sheet in front of lens and light it up from the front "
500 PRINT "Adjust intensity until all channels fall below saturation (about 3500),
510 PRINT "When all 16 channels are within bounds, enter S"
520 PRINT "Channels below 50 will be deleted from the file because they are defective"
530 MD%=3
540 FOR S = 0 TO 15
550 CALL DASH16 (MD%,DIO%(0),FLAG%)
560 LOCATE 8+S,1:PRINT USING"channel ## data = #######";S,DIO%(0)
570 NEXT S
580 Z$=INKEY$
590 IF Z$="S" THEN GOTO 620
600 IF Z$="s" THEN GOTO 620
610 GOTO 540
620 CLS:PRINT "I am busy doing the normalization. DO NOT TOUCH THE LIGHT !!!!"
630 MD%=3:DIO%(0)=0:AV=100
640 FOR L=1 TO AV
650 FOR S = 0 TO 15
660 CALL DASH16 (MD%,DIO%(0),FLAG%)
670 P(S)=P(S)+DIO%(0)
680 NEXT S
690 PEAK=0
700 NEXT L
710 FOR I=0 TO 15
720 P(I)=P(I)/AV
730 IF P(I)>PEAK THEN PEAK = P(I)
740 NEXT I
750 OPEN "O",1,"NORM",2048
760 FOR I=0 tO 15
770 IF P(I)<50 THEN P(I)=0
780 IF P(I)<50 THEN PRINT "FIBER # ";I;" REMOVED FROM LIST"
790 IF P(I)<50 THEN GOTO 820
800 'GENERATING THE NORMALIZATION MULTIPLIER
810 P(I)=PEAK/P(I)
820 PRINT#1,P(I);
830 NEXT I
840 CLOSE
850 PRINT: INPUT "NUMBER OF SAMPLES TO AVERAGE ? ",NS
860 PRINT
870 OPEN "I",1,"NORM"
880 OPEN "I",2,"CAL"
```

```
890 DIM AZ(16):DIM EL(16)
900 DIM ND(16)
910  FOR K=0 TO 15
920  INPUT #1,ND(K)
930 INPUT #2,AZ(K):INPUT #2,EL(K)
940 REM PRINT "normalization operator";ND(K);
950  NEXT K
960  CLOSE
970 INPUT "DEFINE SATURATION LEVEL (¬4000) = ",SAT
980 'GO GET CALIBRATION AND PIXEL SENSITIVITY DATA
990 GOSUB 1960
1000 'taking data RETURN TO THIS POINT **************************************
1001 FOR L=0 TO 15
1002 AR(L)=0
1003 NEXT L
1010 MD%=3
1020 DIO%(0)=0
1030 FOR R=0 TO NS
1040 FOR Z = 0 TO 15
1050 CALL DASH16 (MD%,DIO%(0),FLAG%)
1060 AR(Z)=AR(Z)+DIO%(0)
1070 NEXT Z
1080 NEXT R
1090 FOR I=0 TO 15
1100 AR(I)=AR(I)/NS
1110 NEXT I
1111 PRINT AR(15)
1120 T=0
1130 FOR I=0 TO 15
1140 IF AR(I) > SAT THEN AR(I)=0
1150 'ZEROING OUT DEFECTIVE FIBERS
1160 IF ND(I)=0 THEN AR(I)=0
1170 IF AR(I) > 1 THEN T=T+1
1180 REM PRINT "valid input data";AR(I);
1190 NEXT I
1195 CLS
1200 PRINT " SCAN CHANNELS = ";T
1210 IF T>2 THEN GOTO 1270
1220 PRINT "NOT ENOUGH POINTS. YOU ARE EITHER TOO WEAK OR TOTALY SATURATED."
1230 Z$=INKEY$
1240 IF Z$="S" THEN END
1250 IF Z$="s" THEN END
1260 GOTO 1030
1270 'NORMALIZING THE AR(I) SENSOR DATA
1280 FOR K=0 TO 15
1290 AR(K)=AR(K)*ND(K)
1300 REM PRINT "normalized data";AR(K);
1310 NEXT K
1320 'find the largest three locator in AR(K) array TOP3(0) is largest
1330 TOP3(0)=0:TOP3(1)=0:TOP3(2)=0
1340 MAX=0
1350 FOR J=0 TO 15
1360 TR(J)=AR(J)
1370 REM PRINT TR(J);
1380 NEXT J
1390 FOR V=0 TO 15
1400 IF TR(V)>MAX THEN TOP3(0) = V
1410 MAX = TR(TOP3(0))
1420 NEXT V
1430 TR(TOP3(0))=0
1440 MAX=0
1450 FOR V=0 TO 15
1460 IF TR(V)>MAX THEN TOP3(1) = V
1470 MAX=TR(TOP3(1))
1480 NEXT V
1490 TR(TOP3(1))=0
1500 MAX = 0
1510 FOR V=0 TO 15
1520 IF TR(V)>MAX THEN TOP3(2)=V
1530 MAX = TR(TOP3(2))
1540 REM PRINT TR(V);
1550 NEXT V
1560 'PRINT AR(TOP3(0)),AR(TOP3(1)),AR(TOP3(2))
1570 'normalize these three
1580 AR(TOP3(1))=AR(TOP3(1))/AR(TOP3(0))
1590 AR(TOP3(2))=AR(TOP3(2))/AR(TOP3(0))
1600 AR(TOP3(0))=1
1610 PRINT AR(TOP3(0)),AR(TOP3(1)),AR(TOP3(2))
1620 'algorithm for az/el of point source
1630 PO=TOP3(0):P1=TOP3(1):P2=TOP3(2)
1670 'differentials
1680 DELA=EL(P1)-EL(PO)
1690 DELB=EL(PO)-EL(P2)
1700 DAZA=AZ(P1)-AZ(PO)
1710 DAZB=AZ(P2)-AZ(PO)
1720 'SCALING OF POSITION ON POINT VECTORS (VERY SIMPLE SCALING)
1730 SCALA=AR(P1)/2
1740 SCALB=AR(P2)/2
```

```
1750 'FIND COORDINATE VALUES FOR EACH LEG
1760 AZA=AZ(PO)+SCALA*DAZA
1770 AZB=AZ(PO)+SCALB*DAZB
1780 ELA=EL(PO)+SCALA*DELA
1790 ELB=EL(PO)-SCALB*DELB
1800 'FIND THE MEAN POSITION
1810 EL=(ELA+ELB)/2
1820 AZ=(AZA+AZB)/2
1890 'CLS
1900 PRINT "AZUMITH    - ";AZ
1910 PRINT "ELEVATION - ";EL
1920 Z$=INKEY$
1930 IF Z$="s" OR Z$="S" THEN GOTO 1950
1940 GOTO 1000
1950 END
1960 OPEN "I",3,"CIR"
1970 DIM A(16),N(16)
1980 INPUT#3,A(0),N(0)
1990 OPEN "I",2,"CAL"
2000 FOR I=0 TO 15
2010 INPUT#2,AZ(I),EL(I)
2020 NEXT I
2030 CLOSE
2040 RETURN
```

APPENDIX D

SOFTWARE LISTING FOR TWO-POINT DETECTION

```
10 REM ************* TWO POINT RESOLUTION ALGORITHM *****************
20 REM STEVEN A. MARLOW  APRIL 23,1987 REVISED MAY 11,1987
30 REM THIS PROGRAM WILL TAKE THE INTENSITY VALUES FOR 16 FIBERS
40 REM AND SORT ACCORDING TO INTENSITY FROM LOWEST TO HIGHEST.
50 REM IT THEN DETERMINES IF ONE OR TWO POINTS ARE ILLUMINATING THE
60 REM FIBERS. IT WILL THEN CALCULATE THE POSITION OF THE POINT(S).
70 REM *************************************************************
80 REM  INPUT VARIABLES :
90 REM                    AZ(K)=AZIMUTH POSITION OF FIBER K IN mm.
100 REM                    EL(K)=ELEVATION POSITION OF FIBER K IN mm.
110 REM                   AR(K)=IRRADIANCE VALUE FOR FIBER K.
120 REM                   NG=INDEX OF REFRACTION OF GRIN LENS (ON-AXIS)!
130 REM                   A=GRADIENT LENS QUADRATIC INDEX CONSTANT.
140 REM CALCULATED VALUES :
150 REM          S(I)=INTENTSITY VALUES ORDERED FROM LOW TO HIGH (0-15)0!
160 REM           AZR(I)=AZIMUTH OF FIBER I IN RADIANS.
170 REM           ELR(I)=ELEVATION OF FIBER I IN RADIANS.
180 REM           F(I)= FIBER NUMBER CORRESPONDING TO S(I)0!
190 REM           SEP= DISTANCE SEPERATING PIXELS
200 REM LASER3 (THE CODE DR. ROY WALTERS DEVELOPED) IS USED AS A
210 REM SUBROUTINE TO DETERMINE POINT LOCATION.
220 REM ***************************************************************
230 REM ******************** DIMENSION STATEMENTS ************************
240 DIM S(16),AR(16),AZ(16),AZR(16),EL(16),ELR(16),F(16),L(16),TR(15)
250 DIM DIO%(8),P(16),ND(16),A(16),N(16)
260 PI=3.14159
270 INPUT "WHAT IS FIBER DIAMETER (mm) ? ",FPHI
280 INPUT "WHAT IS QUADRATIC GRADIENT INDEX CONSTANT ? ",A
285 INPUT "ENTER GRIN LENS ON-AXIS REFACTIVE INDEX",NG
290 INPUT "DO YOU WANT MODEL(ENTER 0) OR HARDWARE(ENTER 1) INPUTS?",OP
300 IF OP=0 THEN GOTO 1650
310 REM ********************  INPUT STATEMENTS ***************************
320 CLS
330 CLEAR,49152!
340 SCREEN,0,0,0:KEY OFF
350 DEF SEG=0
360 SG=256*PEEK(&H511)+PEEK(&H510)
370 SG=SG+49152!/16
380 DEF SEG=SG
390 BLOAD "DASH16.BIN",0
400 DIO%(0)=768:DIO%(1)=2:DIO%(2)=3
410 DASH=0
420 FLAG%=0
430 MD%=0
440 CALL DASH16 (MD%,DIO%(0),FLAG%)
450 REM SET CHANNEL SCAN LIMITS
460 MD%=1
470 DIO%(0)=0
480 DIO%(1)=15
490 FOR N=2 TO 4:DIO%(N)=0:NEXT N
500 FLAG%=X
510 CALL DASH16 (MD%,DIO%(0),FLAG%)
520 FOR N=0 TO 4
530 DIO%(N)=0
540 NEXT N
550 FLAG%=0
560 PRINT "THIS PROGRAM GIVES THE AZIMUTH AND ELEVATION (DEGREES) OF A SINGLE "
570 PRINT "OR TWO LASER SOURCES. DATA IS BASED ON COORDINATE INPUTS TO THE "
580 PRINT "CALIB PROGRAM. RUN CALIB FIRST TO ESTABLISH COORDINATE SYSTEM."
590 PRINT "USE ONLY STEDY STATE LIGHT SOURCES. THE PROGRAM USES SIGNAL"
600 PRINT "AVERAGING FOR NOISE REDUCTION. THIS PROGRAM RUNS ON HARD DISC C"
610 PRINT
620 PRINT "                    ******************************"
630 PRINT "                    *   PERFORM NORMALIZATION    *"
640 PRINT "                    ******************************"
650 PRINT
660 PRINT "IF YOU HAVE NOT CHANGED FIBER OPTIC CONNECTORS THIS STEP IS "
670 PRINT "NOT NECESSARY. "
680 INPUT "DO YOU WISH TO NORMALIZE? ",NORM$
690 CLS
700 IF NORM$="N"  THEN GOTO 1100
710 IF NORM$="n"  THEN GOTO 1100
720 PRINT "Place diffusion screen in front of lens and light it up from the "
730 PRINT "front. Adjust intensity until all channels fall below saturation "
740 PRINT "(about 3500),but are above about 50.
750 PRINT "When all 16 channels are within bounds, enter S"
760 PRINT "Channels below 50 will be deleted from the file because they are"
770 PRINT "defective."
780 MD%=3
790 FOR S=0 TO 15
800 CALL DASH16 (MD%,DIO%(0),FLAG%)
810 LOCATE 8+S,1:PRINT USING"channel ## data = #######";S,DIO%(0)
820 NEXT S
830 Z$=INKEY$
840 IF Z$="S" THEN GOTO 870
850 IF Z$="s" THEN GOTO 870
860 GOTO 790
870 CLS:PRINT "I am busy doing the normalization. DO NOT TOUCH THE LIGHT!!"
```

```
880 MD%=3:DIO%(O)=O:AV=100
890 FOR L=1 TO AV
900 FOR S=O TO 15
910 CALL DASH16 (MD%,DIO%(O),FLAG%)
920 P(S)=P(S)+DIO%(O)
930 NEXT S
940 PEAK = O
950 NEXT L
960 FOR I=O TO 15
970 P(I)=P(I)/AV
980 IF P(I)>PEAK THEN PEAK=P(I)
990 NEXT I
1000 OPEN "O",1,"NORM",2048
1010 FOR I=O tO 15
1020 IF P(I)<50 THEN P(I)=O
1030 IF P(I)<50 THEN PRINT "FIBER # ";I;" REMOVED FROM LIST"
1040 IF P(I)<50 THEN GOTO 1070
1050 REM GENERATING THE NORMALIZATION MULTIPLIER
1060 P(I)=PEAK/P(I)
1070 PRINT#1,P(I);
1080 NEXT I
1090 CLOSE
1100 INPUT "NUMBER OF SAMPLES TO AVERAGE ?",NS
1110 PRINT
1120 OPEN "I",1,"NORM"
1130 OPEN "I",2,"CAL"
1140 FOR K=O tO 15
1150 INPUT #1,ND(K)
1160 INPUT #2,AZR((K):INPUT #2,ELR(K)
1170 REM PRINt "NORMALIZATION OPERATOR ",ND(K)
1180 NEXT K
1190 CLOSE
1200 INPUT "DEFINE SATURATION LEVEL (4000) =",SAT
1210 REM GET CALIBRATION AND SENSITIVITY DATA
1220 GOSUB 4200
1230 REM TAKING DATA RETURN TO THIS POINT
1240 FOR L=O TO 15
1250 AR(L)=O
1260 NEXT L
1270 MD%=3
1280 DIO%(O)=O
1290 FOR R=O TO NS
1300 FOR Z=O TO 15
1310 CALL DASH16 (MD%,DIO%(O),FLAG%)
1320 AR(Z)=AR(Z)+DIO%(O)
1330 NEXT Z
1340 NEXT R
1350 FOR I=O TO 15
1360 AR(I)=AR(I)/NS
1370 NEXT I
1380 PRINT AR(15)
1390 T=O
1400 IF AR(I)>SAT THEN AR(I)=O
1410 REM ZEROING OUT DEFECTIVE FIBERS
1420 IF ND(I)=O THEN AR(I)=O
1430 IF AR(I)>1 THEN T=T+1
1440 REM PRINT "VALID INPUT DATA ",AR(I)
1450 NEXT I
1460 CLS
1470 PRINT "SCAN CHANNELS = ";T
1480 IF T>2 THEN GOTO 1540
1490 PRINT "NOT ENOUGH POINTS. YOU ARE EITHER TOO WEAK OR SATURATED."
1500 PRINT "HIT S TO QUIT"
1510 IF Z$="S" THEN END
1520 IF Z$="s" THEN END
1530 GOTO 1290
1540 REM NORMALIZING THE AR(I) SENSOR DATA
1550 FOR I=O TO 15
1560 AR(I)=AR(I)*ND(I)
1570 REM PRINT "NORMALIZED DATA";AR(I);
1580 NEXT I
1590 FOR I=O TO 15
1600 AZ(I)=(AZD(I)/NG*A)*PI/180
1610 EL(I)=(ELD(I)/NG*A)*PI/180
1620 NEXT I
1630 GOTO 1830
1650 FOR K= O TO 15
1660 PRINT "WHAT IS AZ FOR FIBER # K",K
1670 INPUT "ENTER VALUE IN DEGREES ",AZ(K)
1680 PRINT "WHAT IS EL FOR FIBER # K",K
1690 INPUT "ENTER VALUE IN DEGREES ",EL(K)
1700 AZR(K)=AZ(K)*3.1415/180
1710 ELR(K)=EL(K)*3.1415/180
1720 AZ(K)=AZR(K)/(NG*A)
1730 EL(K)=ELR(K)/(NG*A)
1740 NEXT K
1750 FOR K=O TO 15
1760 PRINT "WHAT IS PIXEL VALUE FOR FIBER # K",K
```

```
1770 INPUT "ENTER INTENSITY VALUE",AR(K)
1780 NEXT K
1830 FOR I=0 TO 15
1840 S(I)=AR(I)
1850 F(I)=I
1860 NEXT I
1870 REM *********************************************************************
1880 REM ARRANGE S(I) INTENSITY ARRAY FROM LOWEST VALUE TO HIGHEST
1890 REM S(0)=LOWEST INTENSITY VALUE : S(15)=HIGHEST INTENSITY VALUE
1900 REM F(I)=FIBER # CORRESPONDING TO THAT INTENSITY VALUE
1910 FOR I=0 TO 14
1920          FOR J=I TO 15
1930 IF S(J)<S(I) THEN T=S(J) :S(J)=S(I) :S(I)=T :F=F(J) :F(J)=F(I) :F(I)=F
1940           NEXT J
1950 NEXT I
1960 REM ********************************************************************
1970 REM NORMALIZE THE INTENSITY VALUES
1980 FOR I=0 TO 15
1990 S(I)=S(I)/S(15)
2000 NEXT I
2010 REM *********************************************************************
2020 REM DETERMINE SEPERATION OF HIGHEST TWO INTENSITY FIBERS
2030 REM IF SEPERATION IS GREATER THEN A FIBER DIAMETER THEN TWO POINTS
2040 REM ARE ILLUMINATING THE GRIN LENS. TWO WELL SEPERATED POINTS.
2050 J=F(15)
2060 K=F(14)
2070 SEP=((EL(J)-EL(K))↑2+(AZ(J)-AZ(K))↑2)↑.5
2080 IF SEP>FPHI THEN FLAG=1 ELSE FLAG=0
2090 REM ***********************************************************************
2100 REM DETERMINE IF TWO CLOSE POINTS ARE ILLUMINATING THE FIBER
2110 REM IF IFLAG IS 1 THEN FOUR FIBERS ARE ILLUMINATED AND 2 CLOSE
2120 REM POINTS NEED TO BE DETERMINED.
2130 IF S(15)-S(14)<.27 AND S(12)>.31 THEN IFLAG=1 ELSE IFLAG=0
2140 REM ************************************************************************
2150 REM IF FLAG IS ZERO THEN WE KNOW THAT WE DO NOT HAVE TWO WELL RESOLVED
2160 IF FLAG=0 THEN :GOTO 2980
2170 REM FOR TWO WELL REOSLOVED POINTS DETERMINE THE POSITION OF BOTH POINTS.
2180 PRINT " TWO WELL RESOLVED POINTS BEING CALCULATED"
2190 REM THIS DETERMINES FOR EACH OF THE 6 ILLUMINATED FIBERS HOW MANY
2200 REM ILLUMINATED FIBERS ARE NEXT TO IT. L(I)= # OF ILLUMINATED
2210 REM FIBERS NEAR F(I).
2220 FOR I= 10 TO 15
2230 L(I)=0
2240   FOR J= 10 TO 15
2250   SEP=((EL(F(J))-EL(F(I)))↑2+(AZ(F(J))-AZ(F(I)))↑2)↑.5
2260   IF SEP>FPHI THEN L(I)=L(I)+1 ELSE L(I)=L(I)
2270   NEXT J
2280 NEXT I
2290 REM ***********************************************************************
2300 REM NOW L(I) IS SORTED FROM LOWEST TO HIGHEST. THIS DETERMINES WHICH OF
2310 REM OF THE 6 FIBERS HAVE THE FEWEST ILLUMINATED FIBERS NEAR THEM.
2320 FOR I= 10 TO 14
2330   FOR J= I TO 15
2340   IF L(J)<L(I) THEN :GOTO 2350 ELSE GOTO 2360
2350   S=S(J):S(J)=S(I):S(I)=S:F=F(J):F(J)=F(I):F(I)=F:L=L(J):L(J)=L(I):L(I)=L
2360   NEXT J
2370 NEXT I
2380 REM *********************************************************************
2390 REM THIS PORTION OF THE CODE DETERMINES IF THE SIX ILLUMINATED FIBERS
2400 REM TOUCH OR ARE TOTALLY SEPERATED. IF THEY TOUCH YOU NEED TO DETERMINE
2410 REM WHICH 3 FIBERS ARE GROUPED TOGETHER.
2420 REM IF L(10)=L(15) THEN ALL FIBERS HAVE THE SAME # OF ILLULINATED
2430 REM FIBERS NEAR THEM. SO YOU HAVE TWO GROUPS OF THREE ILLUMINATED
2440 REM FIBERS SEPERATED BY A FIBER (THAT IS NOT ILLUMINATED).
2450 IF L(10)=L(15) THEN LF=1 ELSE LF=0
2460 REM IF THE FIBERS ARE GROUPED TOGETHER GOTO 1230
2470 IF LF =0 THEN :GOTO 2630
2480 REM *******************************************************************
2490 REM FOR TWO POINTS WELL RESOLVED AND THE TWO GROUPS OF THREE FIBERS
2500 REM SEPERATED FIND WHICH FIBERS GO TOGETHER.
2510 JL=0
2520 FOR I=11 TO 15
2530    SEP=((EL(F(10))-EL(F(I)))↑2+(AZ(F(10))-AZ(F(I)))↑2)↑.5
2540 IF SEP>FPHI THEN :GOTO 2570 ELSE JL=JL+1
2550 IF JL=1 THEN F=F(I):F(I)=F(11):F(11)=F:S=S(I):S(I)=S(11):S(11)=S
2560 IF JL=2 THEN F=F(I):F(I)=F(12):F(12)=F:S=S(I):S(I)=S(12):S(12)=S
2570 NEXT I
2580 GOTO 2780
2590 REM ******************** END OF GROUPING FIBERS ****************************
2600 REM ***********************************************************************
2610 REM OUT OF THE SIX FIBERS THAT ARE ALL GROUPED TOGETHER FOUR ARE NOT
2620 REM PLACE THE TWO SEPERATE GROUPS OF TWO IN F(12)&F(13) AND F(14)&F(15)
2630 FOR I= 13 TO 15
2640    SEP=((EL(F(12))-EL(F(I)))↑2+(AZ(F(12))-AZ(F(I)))↑2)↑.5
2650 IF SEP=FPHI THEN F=F(I):F(I)=F(13):F(13)=F:S=S(I):S(I)=S(13):S(13)=S:I=15
2660 NEXT I
2670 REM **********************************************************************
2680 SEP1=((EL(F(12))-EL(F(10)))↑2+(AZ(F(12))-AZ(F(10)))↑2)↑.5
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2690 SEP2=((EL(F(13))-EL(F(10)))↑2+(AZ(F(13))-AZ(F(10)))↑2)↑.5
2700 IF SEP1>FPHI THEN :GOTO 2740
2710 IF SEP2>FPHI THEN :GOTO 2740
2720 S=S(13):S(13)=S(11):S(11)=S:F=F(13):F(13)=F(11):F(11)=F
2730 GOTO 2780
2740 S=S(10):S(10)=S(13):S(13)=S:F=F(10):F(10)=F(13):F(13)=F
2750 REM ****************************************************************
2760 REM THE FIRST POINT IS IN F(10),F(11)&F(12) AND THE SECOND IS IN
2770 REM F(13),F(14)&F(15) SO ARRANGE EACH GROUP ACCORDING TO INTENSITY.
2780  FOR I=10 TO 11
2790   FOR J=I TO 12
2800 IF S(J)<S(I) THEN T=S(J) :S(J)=S(I) :S(I)=T :F=F(J) :F(J)=F(I) :F(I)=F
2810   NEXT J
2820  NEXT I
2830 FOR I=13 TO 14
2840 FOR J=I TO 15
2850 IF S(J)<S(I) THEN T=S(J) :S(J)=S(I) :S(I)=T :F=F(J) :F(J)=F(I) :F(I)=F
2860 NEXT J
2870 NEXT I
2880 REM *****************************************************************
2890 REM NOW CALCULATE THE POSITION OF EACH POINT.
2900 FOR I=10 TO 13 STEP 3
2910 PO=S(I+2):P1=S(I+1):P2=S(I)
2920 ELO=ELR(F(I+2)):EL1=ELR(F(I+1)):EL2=ELR(F(I))
2930 AZO=AZR(F(I+2)):AZ1=AZR(F(I+1)):AZ2=AZR(F(I))
2940 GOSUB 3990
2950 NEXT I
2960 GOTO 4160
2970 REM *********END OF TWO POINT SIX GROUPED FIBER CALCULATION ***********
2980 REM IF FOUR FIBERS ARE ILLUMINATED GOTO 1860
2990 IF IFLAG=1 THEN :GOTO 3580
3000 REM *****************************************************************
3010 REM IF FIVE FIBERS ARE ILLUMINATED GOTO 1590
3020 PRINT "S(11) IS ",S(11)
3030 IF S(11)>.2 THEN :GOTO 3140
3040 REM *****************************************************************
3050 PRINT "ONE POINT CALCULATION "
3060 PO=S(15):P1=S(14):P2=S(13)
3070 ELO=ELR(F(15)):EL1=ELR(F(14)):EL2=ELR(F(13))
3080 AZO=AZR(F(15)):AZ1=AZR(F(14)):AZ2=AZR(F(13))
3090 GOSUB 3990
3100 GOTO 4160
3110 REM ******************************************************************
3120 REM THIS PORTION OF THE CODE FINDS TWO POINTS WHEN FIVE FIBERS ARE ON.
3130 REM DETERMINE WHICH FIBER TOUCHES ALL OTHER ILLUMINATED FIBERS (L(I)=0).
3140 FOR I= 11 TO 15
3150 L(I)=0
3160   FOR J= 11 TO 15
3170   SEP=((EL(F(J))-EL(F(I)))↑2+(AZ(F(J))-AZ(F(I)))↑2)↑.5
3180   IF SEP>FPHI THEN L(I)=L(I)+1 ELSE L(I)=L(I)
3190   NEXT J
3200 NEXT I
3210 REM ARRANGE L(I) FROM LOWEST TO HIGHEST VALUES. PLACE THE FIBER
3220 REM THAT TOUCHES ALL FOUR FIBERS IN F(11).
3230 FOR I= 11 TO 14
3240   FOR J= I TO 15
3250   IF L(J)<L(I) THEN :GOTO 3260 ELSE GOTO 3270
3260   S=S(J):S(J)=S(I):S(I)=S:F=F(J):F(J)=F(I):F(I)=F:L=L(J):L(J)=L(I):L(I)=L
3270   NEXT J
3280 NEXT I
3290 FOR I= 11 TO 15
3300 PRINT "L F IS ",L(I),F(I)
3310 NEXT I
3320 REM FIND WHICH OF THE OTHER FOUR FIBERS BELONG TOGETHER IN GROUPS OF TWO.
3330 JL=0
3340 FOR I=13 TO 15
3350   SEP=((EL(F(12))-EL(F(I)))↑2+(AZ(F(12))-AZ(F(I)))↑2)↑.5
3360 IF SEP>FPHI THEN :GOTO 3390 ELSE JL=JL+1
3370 IF JL=1 THEN F=F(I):F(I)=F(12):F(12)=F:S=S(I):S(I)=S(12):S(12)=S
3380 IF JL=2 THEN F=F(I):F(I)=F(13):F(13)=F:S=S(I):S(I)=S(13):S(13)=S
3390 NEXT I
3400 REM ARRANGE FIBERS ACCORDING TO INTENSITY
3410 IF S(13)<S(12) THEN T=S(12):S(12)=S(13):S(13)=T:F=F(12):F(12)=F(13):F(13)=F
3420 IF S(11)<1 THEN :STOP
3430 PO=S(11):P1=S(13):P2=S(12)
3440 REM FIND THE POSITION OF THE FIRST POINT.
3450 ELO=ELR(F(11)):EL1=ELR(F(13)):EL2=ELR(F(12))
3460 AZO=AZR(F(11)):AZ1=AZR(F(13)):AZ2=AZR(F(12))
3470 GOSUB 3990
3480 REM ARRANGE FIBERS ACCORDING TO INTENSITY DO SIMPLE SCALING AND FIND
3490 REM SECOND POINT.
3500 IF S(15)<S(14) THEN T=S(14):S(14)=S(15):S(15)=T:F=F(14):F(14)=F(15):F(15)=F
3510 PO=S(11):P1=S(15):P2=S(14)
3520 ELO=ELR(F(11)):EL1=ELR(F(15)):EL2=ELR(F(14))
3530 AZO=AZR(F(11)):AZ1=AZR(F(15)):AZ2=AZR(F(14))
3540 GOSUB 3990
3550 GOTO 4350
3560 REM ***************** END FIVE FIBER CALCULATION ***********************
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3570 REM **********************************************************************
3580 REM TWO CLOSE POINTS BEING CALCULATED FOR FOUR ILLUMINATED FIBERS
3590 FOR I= 12 TO 15
3600 L(I)=O
3610   FOR J= 12 TO 15
3620   SEP=((EL(F(J))-EL(F(I)))↑2+(AZ(F(J))-AZ(F(I)))↑2)↑.5
3630   IF SEP>FPHI THEN L(I)=L(I)+1 ELSE L(I)=L(I)
3640   NEXT J
3650 NEXT I
3660 FOR I= 12 TO 14
3670   FOR J= I TO 15
3680   IF L(J)<L(I) THEN :GOTO 3690 ELSE GOTO 3700
3690   S=S(J):S(J)=S(I):S(I)=S:F=F(J):F(J)=F(I):F(I)=F:L=L(J):L(J)=L(I):L(I)=L
3700   NEXT J
3710 NEXT I
3720 AR(1)=S(15):AR(2)=S(13)*.8:AR(3)=S(12)*.8
3730 F(1)=F(15):F(2)=F(13):F(3)=F(12)
3740 FOR I=1 TO 2
3750     FOR J=I TO 3
3760   IF AR(J)<AR(I) THEN A=AR(I):AR(I)=AR(J):AR(J)=A:F=F(J):F(J)=F(I):F(I)=F
3770     NEXT J
3780 NEXT I
3790 PO=AR(3)/AR(3):P1=AR(2)/AR(3):P2=AR(1)/AR(3)
3800 ELO=ELR(F(3)):EL1=ELR(F(2)):EL2=ELR(F(1))
3810 AZO=AZR(F(3)):AZ1=AZR(F(2)):AZ2=AZR(F(1))
3820 GOSUB 3990
3830 AR(1)=S(14)/.8:AR(2)=S(13)*.8:AR(3)=S(12)*.8
3840 F(1)=F(14):F(2)=F(13):F(3)=F(12)
3850 FOR I=1 TO 2
3860    FOR J=I TO 3
3870   IF AR(J)<AR(I) THEN A=AR(I):AR(I)=AR(J):AR(J)=A:F=F(J):F(J)=F(I):F(I)=F
3880     NEXT J
3890 NEXT I
3900 PO=AR(3)/AR(3):P1=AR(2)/AR(3):P2=AR(1)/AR(3)
3910 ELO=ELR(F(3)):EL1=ELR(F(2)):EL2=ELR(F(1))
3920 AZO=AZR(F(3)):AZ1=AZR(F(2)):AZ2=AZR(F(1))
3930 GOSUB 3990
3940 GOTO 4160
3950 REM **************** END OF FOUR FIBER TWO POINT CALCULATION *************
3960 REM **********************************************************************
3970 REM ****SUBROUTINE TO DETERMINE LOCATION OF POINT(S)*************
3980 REM ***************** LASER3 CODE *******************************
3990 DELA=EL1-ELO
4000 DELB=ELO-EL2
4010 DAZA=AZ1-AZO
4020 DAZB=AZ2-AZO
4030 SCALA=P1/2
4040 SCALB=P2/2
4050 AZA=AZO+SCALA*DAZA
4060 AZB=AZO+SCALB*DAZB
4070 ELA=ELO+SCALA*DELA
4080 ELB=ELO-SCALB*DELB
4090 EL=((ELA+ELB)/2)*180/PI
4100 AZ=((AZA+AZB)/2)*180/PI
4110 PRINT "PO:P1:P2",PO,P1,P2
4120 PRINT "AZO:AZ1:AZ2",AZO,AZ1,AZ2
4130 PRINT "ELO:EL1:EL2",ELO,EL1,EL2
4140 PRINT "AZ,EL IS ",AZ,EL
4150 RETURN
4160 PRINT "DO YOU WANT TO CONTINUE WITH SAME COORDINANTS"
4170 INPUT "ENTER (1=YES O=NO) ",RAG
4180 IF RAG=1 THEN :GOTO 1750 ELSE END
4190 REM ********************* END OF SUBROUTINE ****************************
4200 REM ********************* START SUBROUTINE ********************************
4210 Z$=INKEY$
4220 IF Z$="S" THEN GOTO 4250
4230 IF Z$="s" THEN GOTO 4250
4240 GOTO 1230
4250 END
4260 OPEN "I",3,"CIR"
4270 INPUT#3,A(O),N(O)
4280 OPEN "I",2,"CAL"
4290 FOR I=O TO 15
4300 INPUT#2,AZR(I),ELR(I)
4310 NEXT I
4320 CLOSE
4330 RETURN
4340 REM ********************** END OF PROGRAM ********************************
4350 END
```

REFERENCES

(1) Baradar, A. 1983. "Spacially Sampled Multi-Aperture Optical System for Robot Vision. Masters Thesis. University of Central Florida.

(2) Schneider, R. 1983. "Energy Transfer Technology: Wide Field Optics Technique". AFATL-TR-83-23.

(3) Walters, R. and G. Boreman. 1986. "White Paper on Multi-Aperture ptical Systems". Department of Electrical Engineering and Communication Sciences. University of Central Florida.

(4) Walters, R. and B. Mathews. 1983. "Aposition Multi-Aperture Optical Systems Operating in Signature and Pseudo Space". Proceedings of the National Aerospace and Electronics Conference. Dayton, Ohio (May 17-19).

(5) Kellog, S. 1982. "Theoretical Modeling for Detectivity on Resolution Comparison of Single Aperture and Multiple Aperture Imaging Systems". Research Report. University of Central Florida.

(6) Mathews, B.E. and R.A. Walters. 1983. "Random Effects on Multi-Aperture Element Density:". Proceedings of the National Aerospace and Electronics Conference. Dayton, Ohio (May 17-19).

(7) Seyrofi, K. 1973. Electro-Optical Systems Analysis. Electro-Optical Research Company.

(8) Boyd, R. 1983. Radiometry and the Detection of Optical Radiation. John Wiley and Sons.

(9) Yariv, A. 1976. Introduction to Optical Electronics. Holt, Rhinehart and Winston.

(10) SELFOC Handbook. 1979. New York: Nippon Sheet Glass America.

(11) Goodman, J. 1968. Fourier Optics. McGraw Hill Book Company. San Francisco, CA.

(12) Wendland, P. and L. Wendland. 1987. "Using Far Field Scanning as a Diagnostic Tool". Fiber Optic Product News (May).

(13) Cherin, Allen. 1983. An Introduction to Optical Fibers. New York: McGraw Hill.

REFERENCES - Continued

(14) Barnoski, M. 1981. Fundamentals of Optical Fiber Communications. Academic Press.

(15) Hecht, E. and A. Zajac. 1979. Optics. Addison-Wesley Publishing Company, Inc., Reading, MA.