To the Graduate Council:

I am submitting herewith a thesis written by Jimmy Dean Sisco entitled "A Feasibility Study on the Use of a Low-Resolution Infrared Detector Array for Monitoring the Output Beam of a High-Power Laser". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters, with a major in Engineering Science and Mechanics.

L. Montgomery Smith

L. Montgomery Smith, Major Professor

We have read this thesis
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"A Feasibility Study on the Use of a Low-Resolution Infrared Detector Array for Monitoring the Output Beam of a High-Power Laser"

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jimmy Dean Sisco

Spring 1996

Dedicated to my Wife

R. Loyce Sisco

Acknowledgments

I would like to thank my major professor, Dr. Monte Smith, for his guidance and patience. I would also like to thank the thesis review committee members, Dr. Mary McCay and Dr. Reinhard Menzel, for their comments and assistance in the completion of this thesis. I would like to thank a friend and co-worker Mr. Sidney Steely for his valuable comments and assistance that enabled myself to stay on track. Finally I would like to thank my wife, R. Loyce Sisco, without whose patience, child rearing, and encouragement over the years this thesis would not have been possible.

ABSTRACT

The University of Tennessee Space Institute uses a 3kW laser to weld and cut materials. The laser's spot focus distance, spot location, and output changes during a full day of operation potentially producing an uncertain weld strength and a variation in cutting thickness. Therefore, it is desirable to monitor the laser beam output to determine if changes are occurring in the operating Gaussian modes.

This research determined if a 32 by 32 detector array can distinguish between mixed high-order Laguerre and Hermite Gaussian laser beam modes. A software program was written to allow a User to generate Laguerre and Hermite Gaussian beam modes or mixed Laguerre and Hermite Gaussian beam modes with the capability to change the beam size, non-complex amplitude, and rotation aspects. The program further allows the User to display the generated file on a simulated 32 by 32 detector array in black and white or color shades. The program compares single or mixed Gaussian beam modes (reference set) to single or mixed Gaussian beam modes with added Gaussian noise (test sets). A correlation between the reference set and various test sets were performed as an identification method.

It was concluded that the 32 by 32 detector array can determine the dominant Gaussian beam mode operating in a low noise laser. However,

identifying other lower amplitude modes is unlikely. In addition, similar modes with rotational differences between the reference and test sets were tested and failed to meet the acceptable correlation criterion.

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CHAPTER I

INTRODUCTION

The University of Tennessee Space Institute, Center for Laser Applications has a 3kW CO_2 laser used primarily for welding and cutting materials. During the welding or cutting process, it is important that the laser operating mode be stable to provide an accurate cut or weld. The laser beam welding or cutting characteristics are determined by the time delays between pulses, the mode structure for imaging distances, and focused energy per area. In the past, the laser beam position has been reported to drift one-half of an inch after a full day of operation time [1]. The shift in beam location could be attributed to excessive heating of the laser cavity mirrors causing movement and/or warpage to the mirrors. Any major mirror movement will cause the laser cavity resonance to become unstable and the laser beam output to discontinue. Any minor mirror movement or change in shape will maintain a stable laser cavity but introduce other lasing modes. These modes will be imaged by the focusing optics which will shift/change the spot focus distance, spot location, and output, potentially producing an uncertain weld strength and a variation in cutting thickness.

It has been proposed to use a pyroelectric detector array to monitor and determine the Gaussian beam modes operating in the 3kW laser. An on-line monitoring system would allow an operator to make necessary operating parameter corrections and/or re-align the laser mirrors to set the desired mode structure. The conceptual test configuration is shown in Figure 1. The proposed detector is available in a limited range of sizes, i.e., 16 by 16, 32 by 32, 64 by 64, 128 by 128, 256 by 256, and 512 by 512, with associated ranges in cost. This research investigated the use of a 32 by 32 detector array to resolve the Gaussian beam mode structure by means of a software program.

A software program was written in MS QBASIC [2] to simulate a single or multiple mixed high order Gaussian beam modes projected on a 32 by 32 detector array. The program has the capability to produce Laguerre and/or Hermite Gaussian beam modes. The created modes are displayed as they appear on a projected surface and on a 32 by 32 detector array simulation. After single and mixed mode patterns were created, a correlation study was performed to compare the calculated reference beams to the other calculated beam patterns with added Gaussian noise. The correlation process was the basis used in determining if a 32 x 32 detector array can distinguish between different mode structures.

The software program emulates a detector's physical size and computes the correlation coefficient to calculated data files representing a reference beam and a test beam (a reference beam with noise added). Ultimately, the software program written for this research can be used to read in a data file from an array and then correlate it with reference files to determine the Gaussian beam mode structure.

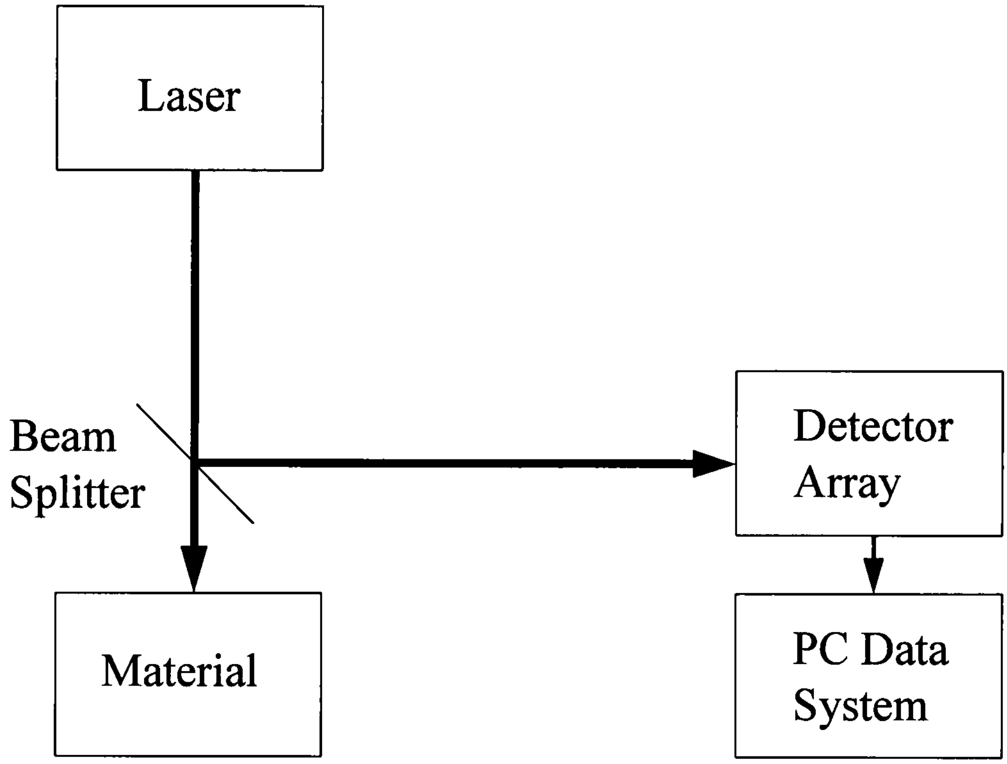


Figure 1. Conceptual Test Configuration

The goal of this research was to develop a system that allows a User to sample a Gaussian laser beam and identify the operating mode by means of visual and correlation identification. The User would use the lookup figures, included in Chapter III, as a preliminary visual match and further perform a correlation process to confirm a mode match.

Throughout this document the word "User" denotes a person operating the mode calculation program. The asterisk character, "*", represents any or all filename extensions. The term "filename" in "filename.*" denotes any file defined by the User. Chapter II states the physical parameters and assumptions used for the simulation of a 32 by 32 detector array and the high powered laser. Chapter III begins with a software program overview. The overview describes the programs capabilities and limits. The startup section describes the file listings and startup operation. Methods used in creating, plotting, and mixing arrays are also discussed. And last, the correlation process is explained. Chapter IV covers the results of the correlation process and rotational test images relative to reference images are discussed. Chapter V summarizes the conclusion of this research and provides recommendations for further actions.

CHAPTER II

DETECTOR AND LASER DESCRIPTION

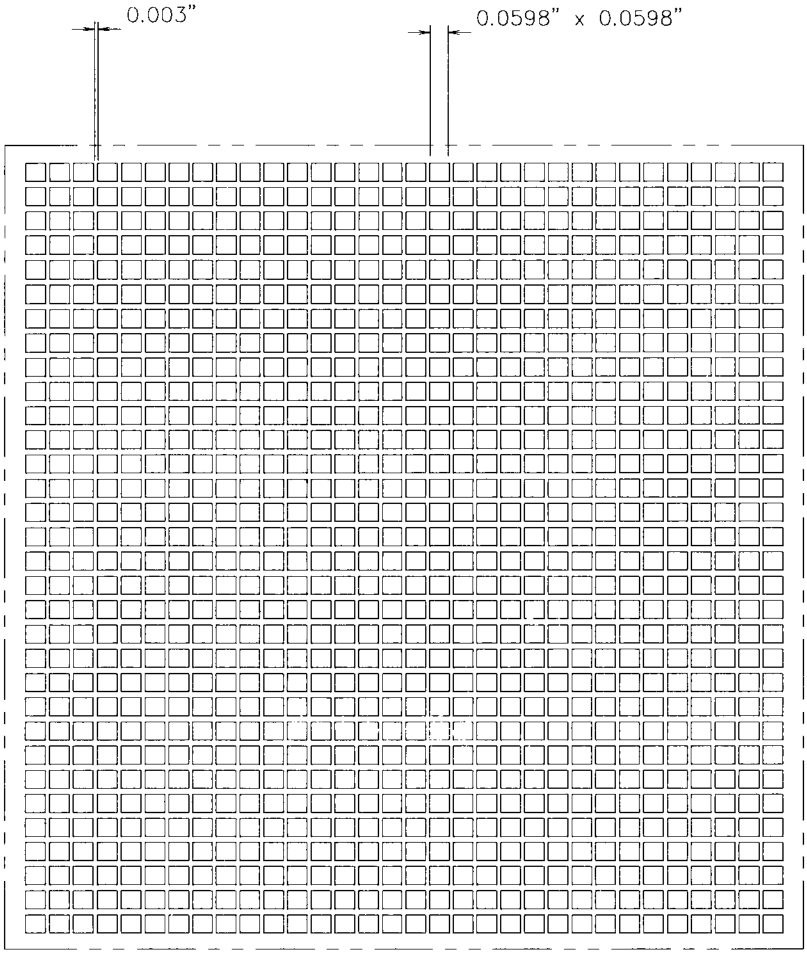
The detector array studied in this research is a Spiricon Model LMP-32x32-161. The square array contains 1,024 pixels in a 32 row by 32 column configuration. The active detector area is 2 x 2 inches square (51.2 x 51.2 mm). Each element size is 0.0598 x 0.0598 inches (1.520 x1.520 mm) spaced such that a 0.0031 inch (0.080 mm) gap exists between the pixels [3]. A summary of the detector specifications are listed in Table 1. The detector array pixel spacing is represented in Figure 2.

University of Tennessee Space Institute, Tullahoma, has a Rofin-Sinar RS3000 fast axial flow CO_2 laser that can deliver a maximum continuous wave power of 3,700 watts. The laser is excited at 27.12 MHz to produce an operating wavelength of 10.6 microns. The reflective output optics have a focal length of 150 mm, F/6.0. The typical operating modes of the laser is Laguerre-Gaussian $TEM_{(00)}$, $TEM_{(10)}$, and $TEM_{(20)}$. The laser is modulated at 5 kHz and can provide 7 to 100 percent of continuous power, 260 watts to 3,700 watts respectively. The laser operated in the pulsed mode is excited at 27.12 MHz and can be gated at frequencies up to 25 kHz. The laser operated in the pulsed mode is fixed at 3,700 watts. The duty cycle can be adjusting by the on/off pulse times.

Table 1. Detector Array Specifications [3]

Model	LMP-32x32-161
1. Number of Elements	1024
2. Active Area	51.2x51.2 mm 2x2 inches
3. Resolution	1.600 mm
4. Element Dimensions	1.520x1.520 mm
5. Gap Between Elements	.080 mm
6. $LiNbO_3$	
7. Spectral Response*	less than .1 to 1000 μm
8. Clock Rate	4 μsecs/elements
9. Power Requirement	+10 to +15 volts
10. Operating Temperature	5 to 45 °C
11. Uniformity of Response	±5 %
Chopped CW Operation	
1. Responsivity, $\Re_v$	200 V/W/element
2. Noise	150 μV
3. Sensitivity**	750 nW
4. Noise Equivalent Power (NEP)	140 $nW/Hz^{1/2}$
5. Saturation Power	7.5 mW/element 300 mW/cm^2
6. Dynamic Range	10^4
7. Maximum Average Power	5 W .2 W/cm^2
Pulsed Operation	
1. Responsivity, $\Re_v$	3.3×10^4 V/J/element
2. Noise	1 mV
3. Sensitivity**	30 nJ/element
4. Saturation Energy	45 μJ/element 1.8 mJ/cm^2
5. Damage Threshold***	20 mJ/cm^2
6. Laser Pulse Width Minimum Maximum	 1 ps 50 ms
7. Maximum Pulse Rate Repetition Rate or Chopping Frequency	100 Hz
Mechanical Specifications	
Dimension	4.5Hx4.5Wx2.75D inches
Weight	2.4 lbs. (1.1kg)
Detector Array Position (center of array)	centered, 0.565 inches behind front plate.

* Specific range determined by window: BaF_2, ZnSe, Qtz, Poly, Ge.
** Can be improved by square root of number of frames averaged in Beam Link.
*** Based on damage threshold and saturation curve of pyroelectric detector array versus input pulsewidth



32 by 32 Detector Array
1024 Pixels Total

Figure 2. Detector Array Pixel Spacing

The average output power is dependent upon the duty cycle of the laser defined by:

$$\tau_{duty} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}}$$

The average power is equal to the average pulsed power times the duty cycle [4].

The pulse repetition are much faster than the integration period of the detector array. Therefore, it is assumed the projected laser beam will be seen as a continuous beam by the detector array. The laser beam projected onto the detector array must be chopped at a selected frequency (10 to 15 Hertz) to yield a response signal, since the pyroelectric detector can only detect a change in signal.

CHAPTER III

SOFTWARE DESIGN

OVERVIEW

The software program generates intensity data files for Hermite and Laguerre Gaussian beam modes ranging from $TEM_{(0,0)}$ to $TEM_{(7,7)}$. A combination of the Hermite and Laguerre mode files can be mixed, rotated, have the non-complex amplitude varied, and then plotted. The single or mixed Hermite and Laguerre mode files can be viewed on a computer screen in 64 gray levels or 64 color shades. The displayed output provides a representation of simulated data acquired by a 32 by 32 detector array and a visual display of the intensity distribution. The generated files are also used in a correlation process that is described later in this chapter. The Main Menu allows the User to list, create, plot, mix and correlate Gaussian beam modes. The Main Menu provides a User friendly interface to all the available options as shown in Figure 3.

```
***************************************************************************
*         This program creates and plots Gaussian-Laguerre and           *
*      Gaussian-Hermite intensity profiles on a 32x32 Pixel Array        *
***************************************************************************

     ***************************************************************
     *                          Main Menu                          *
     ***************************************************************
     *                                                             *
     *                                                             *
     *                  1) List Existing Arrays                    *
     *                                                             *
     *                  2) Change Setup File                       *
     *                                                             *
     *                  3) Create Array                            *
     *                                                             *
     *                  4) Plot Array                              *
     *                                                             *
     *                  5) Mix Existing Arrays                     *
     *                                                             *
     *                  6) Correlation Process                     *
     *                                                             *
     *                  7) Quit                                    *
     *                                                             *
     *              Choose one of the following.                   *
     *                                                             *
     ***************************************************************
?
```

Figure 3. Main Menu

STARTUP

The program files "MODES.EXE" and "STARTUP.DAT" must be installed in the same directory in order to run the program. The computer software should be a DOS-based system, version 3.2 or greater [2]. The hardware requirements are a IBM PC compatible 386 minimum (recommend 486), VGA monitor, and at least 20 megabytes of hard drive space. All mode files are saved on the hard drive for future use, however, they can be deleted and re-created at a later date. Running the program will prompt the User with a

Main Menu screen. The first option, "List Existing Arrays", enables the User to view the mode files present on the computer's hard drive. The files can be easily identified by using the file notation discussed later in this chapter. The second option, "Change Setup File", allows the User to view and change the setup parameters in "STARTUP.DAT" file. These parameters are used in calculating the Hermite or Laguerre Gaussian beam modes. The parameters are amplitude (Amp), Gaussian beam waist $w(z)$, and angular rotation (theta). The amplitude (Amp) is the mode power (watts) to be used to create a file. For this research, the amplitude is defaulted to 1 (arbitrary units). The amplitude parameter is intended to be used during the mixing array option and will be discussed later in this chapter. The Gaussian beam waist $w(z)$ is the beam waist size at distance z from the minimum beam waist w_0. The beam waist $w(z)$ is entered as a radius in units of inches, e.g., 0.5 is entered as a radius for a 1 inch beam diameter. For this research, z is the distance the detector array is placed from the beam minimum waist w_0. The angular rotation allows the User to create a rotated Gaussian beam mode file in case the actual array or laser beam is rotated. The rotation units are entered in as degrees, e.g., 23 is entered for a clockwise beam rotation of 23 degrees. All of the parameters are stored in an ASCII file named "STARTUP.DAT" and are required to run the program. The changes by the User inputs in "STARTUP.DAT" become the programs defaults and are retained until the

User changes them again. Figure 4 presents the software structure for file listing and startup parameters.

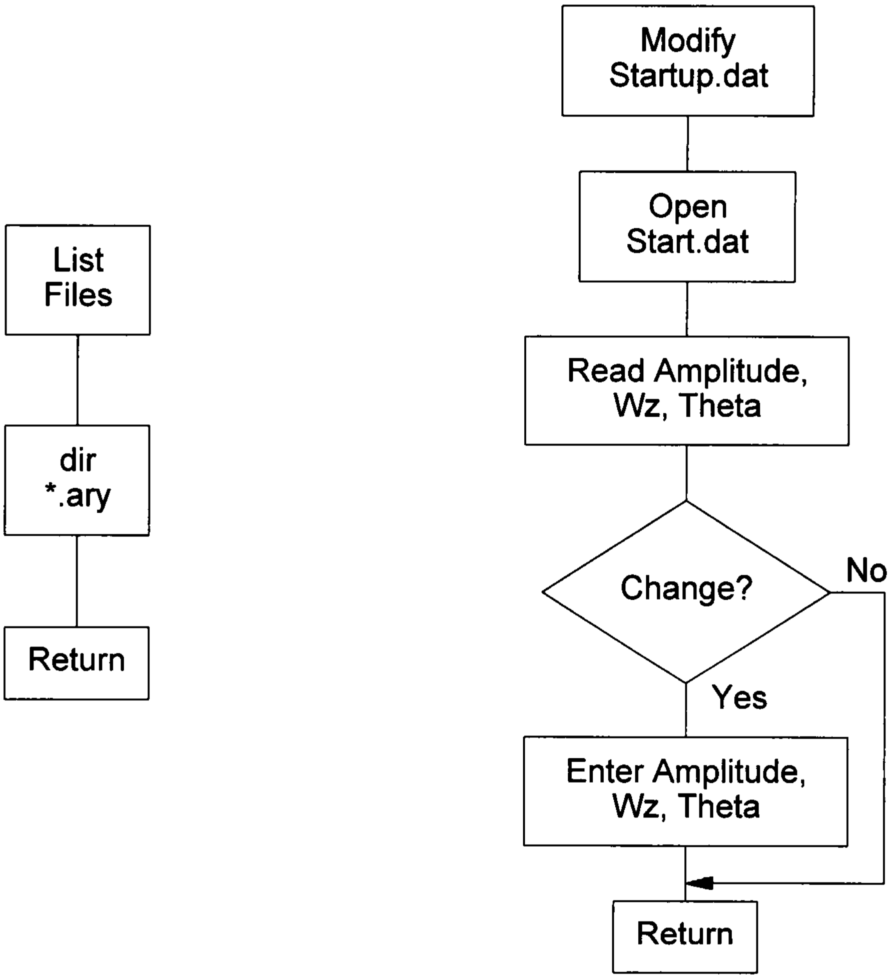


Figure 4. Software Structure for File Listing and Startup Process

CREATING ARRAYS

Newly created files can be Hermite or Laguerre form with any mode structure from $TEM_{(0,0)}$ to $TEM_{(7,7)}$. In the third option, "Create Array", the User is asked to enter in a specific filename to be begin the file generation process. For simplicity, the following filename notation is recommended:

Filename Notation S H 1 3 2 3 . dat

Mode (Example: S - Single, M - Mixed)

Type (Example: H - Hermite, L - Laguerre)

$TEM_{(m,n)}$ Mode (Example: 13 $\Rightarrow$ m = 1, n = 3)

Angular Orientation (Example: 23 = 23 degrees)

File Extension (Example: .dat is a startup file)

After entering the filename, the User chooses 1 for Hermite or 2 for Laguerre Gaussian beam type and $TEM_{(0,0)}$ through $TEM_{(7,7)}$ mode type.

The high-order Hermite Gaussian modes are derived in terms of rectangular coordinates in a laser resonate cavity and are mathematically represented by [5] [6] [10]:

$$E_{m,n}(x,y)=\frac{E_0}{w(z)}H_m\left(\frac{\sqrt{2}x}{w(z)}\right)H_n\left(\frac{\sqrt{2}y}{w(z)}\right)\exp\left[\frac{-\left(x^2+y^2\right)}{w^2(z)}\right]\exp\left[\frac{j\pi\left(x^2+y^2\right)}{\lambda R(z)}\right]$$

where E_0 is an arbitrary amplitude constant, z is the distance from the minimum beam waist w_0 within the laser cavity to the point of interest, λ is the laser beam operating wavelength, and $w(z)$ represents the laser spot size at the area of interest and is defined by [5] [6]:

$$w(z)=w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$

The term $R(z)$ is the curvature radius of the beam located at distance z from the minimum beam waist w_0. The minimum beam waist is defined by [5]:

$$w_0=\frac{2\lambda}{\pi\alpha}$$

where α is the angular beam spread in radians between the $\frac{1}{e^2}$ points. The Hermite polynomials, $H_m(x)$ and $H_n(x)$, are given by [7]:

$$H_m(x) = (-1)^m e^{x^2} \frac{d^m}{dx^m}(e^{-x^2})$$

For example, the first eight Hermite polynomials are

$$\begin{aligned}
H_0(x) &= 1 \\
H_1(x) &= 2x \\
H_2(x) &= 4x^2 - 2 \\
H_3(x) &= 8x^3 - 12x \\
H_4(x) &= 16x^4 - 48x^2 + 12 \\
H_5(x) &= 32x^5 - 160x^3 + 120x \\
H_6(x) &= 64x^6 - 480x^4 + 720x^2 - 120 \\
H_7(x) &= 128x^7 - 1344x^5 + 3660x^3 - 1680x
\end{aligned}$$

The light intensity, $I_{m,n}$, projected onto the detector array is defined as [5][6]:

$$I_{m,n} = E \bullet E^*$$

resulting in:

$$I_{m,n}(x,y) = \frac{|E_0|^2}{w^2(z)} H^2{}_m\left(\frac{\sqrt{2}x}{w(z)}\right) H^2{}_n\left(\frac{\sqrt{2}y}{w(z)}\right) \exp\left[\frac{-2\left(x^2+y^2\right)}{w^2(z)}\right]$$

The first 64 Hermite mode intensity patterns are shown in Figures 5 and 6.

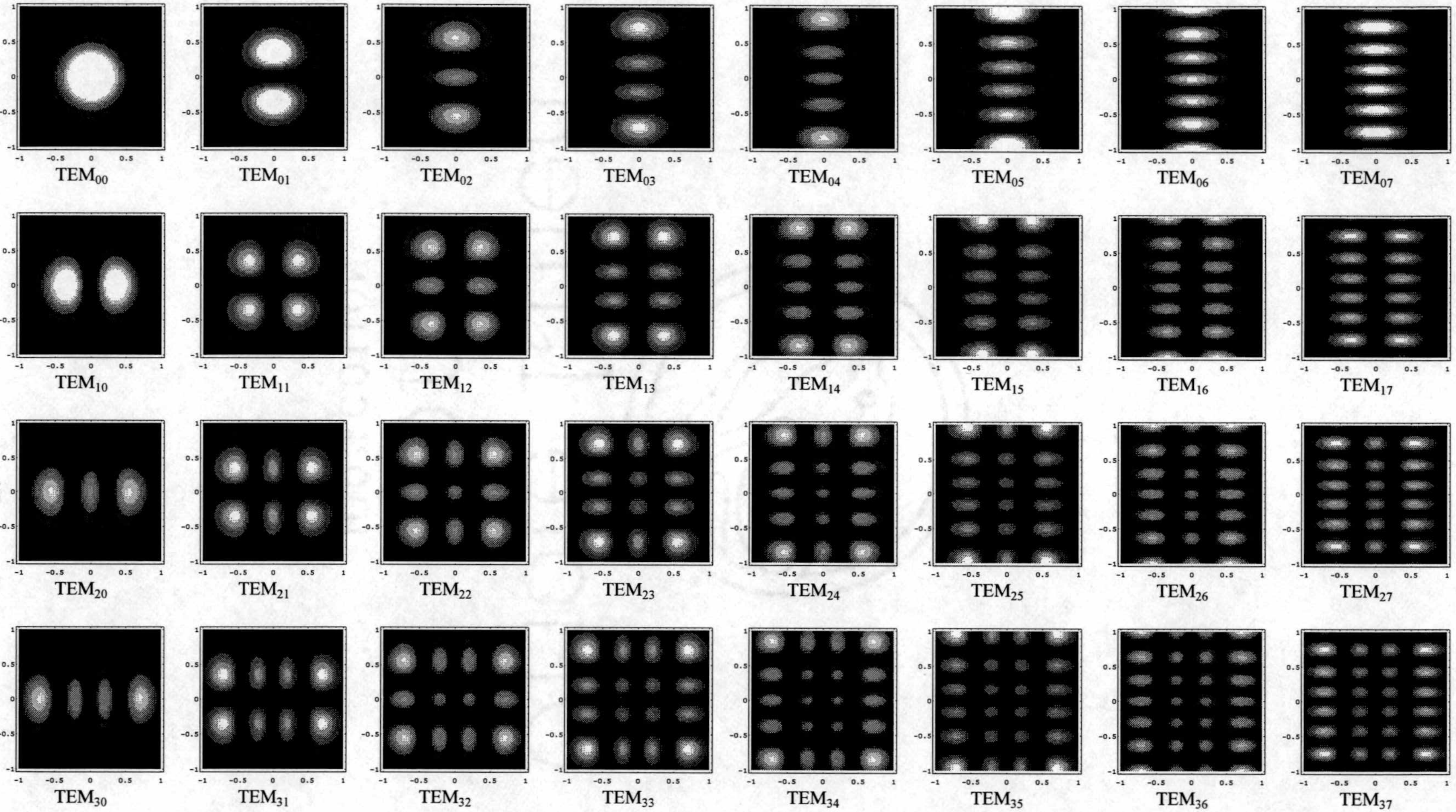


Figure 5. Hermite-Gaussian Modes (Beam Waist Equals 1 Inch).

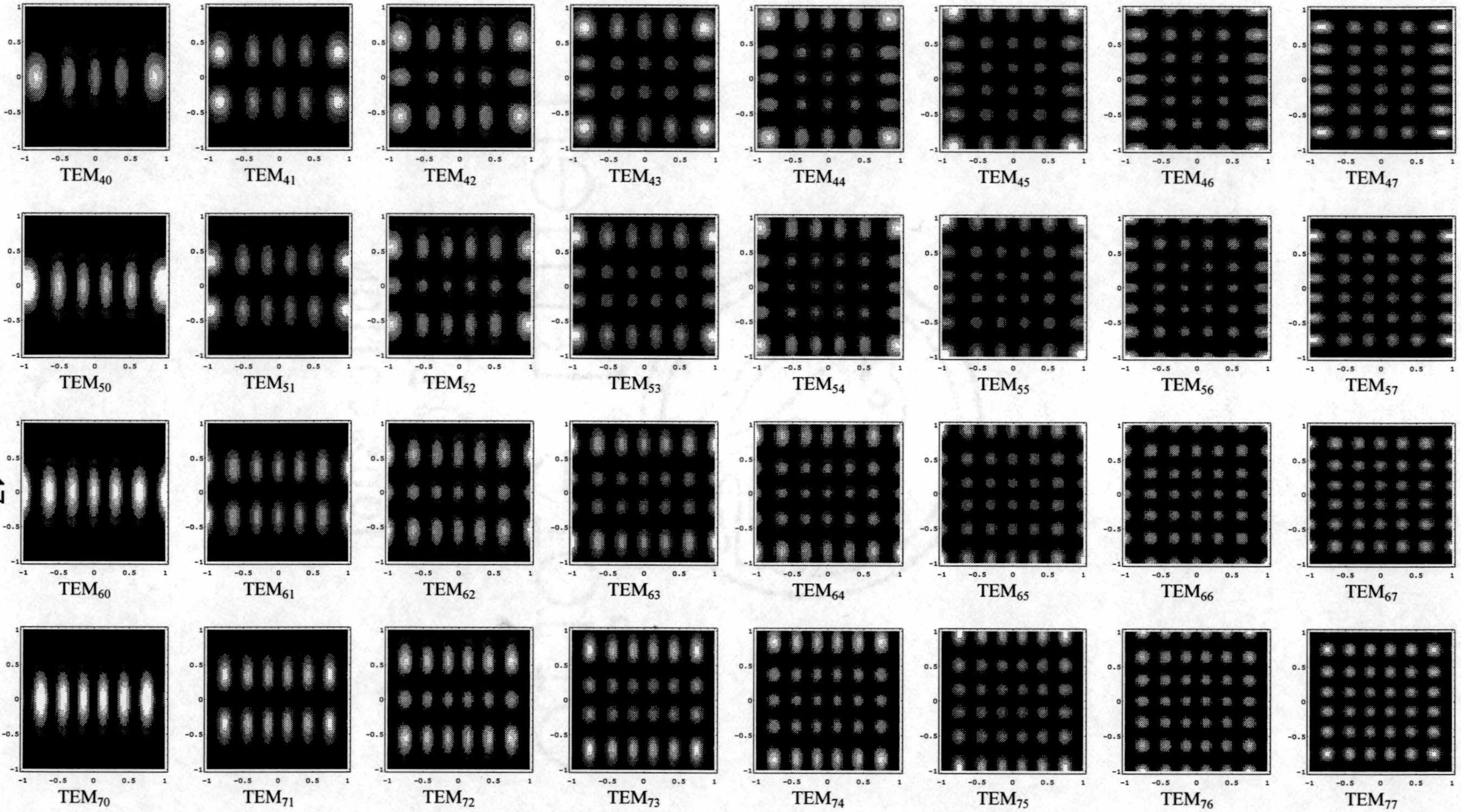


Figure 6. Hermite-Gaussian Modes (Beam Waist Equals 1 Inch).

The high-order Laguerre Gaussian modes are usually derived in terms of cylindrical coordinates in a laser cavity and are mathematically represented by [5][8][10]:

$$E_{p,l}(r,\theta) = \frac{E_0}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{l} L_p^{(l)}\left(\frac{2r^2}{w^2(z)}\right)\cos l\theta \exp\left[\frac{-r^2}{w^2(z)}\right]\exp\left[\frac{j\pi r^2}{\lambda R(z)}\right]$$

where E_0, z, λ, $w(z)$, $R(z)$ are as previously defined. The Laguerre polynomial, $L_p^{(l)}(x)$, for l equal to zero and p any positive integer is defined by [7]:

$$L_p^{(0)}(x) = 1$$

and for l greater than zero

$$L_p^{(l)}(x) = (-1)^l \frac{d^l}{dx^l} L_{p+l}(x)$$

The first 13 Laguerre polynomials are:

$$
\begin{aligned}
&L_p^{(0)}(x) = 1 && \text{for any } p \\
&L_0^{(1)}(x) = 1 - x \\
&L_1^{(1)}(x) = 2 - x \\
&L_2^{(1)}(x) = 3 - x \\
&L_3^{(1)}(x) = 4 - x \\
&L_0^{(2)}(x) = \frac{2 - 4x^2 + x}{2} \\
&L_1^{(2)}(x) = \frac{6 - 6x^2 + x}{2} \\
&L_2^{(2)}(x) = \frac{12 - 8x^2 + x}{2} \\
&L_3^{(2)}(x) = \frac{20 - 10x^2 + x}{2} \\
&L_0^{(3)}(x) = \frac{6 - 18x^2 + 9x^3 - x}{6} \\
&L_1^{(3)}(x) = \frac{24 - 36x^2 + 12x^3 - x}{6} \\
&L_2^{(3)}(x) = \frac{60 - 60x^2 + 15x^3 - x}{6} \\
&L_3^{(3)}(x) = \frac{120 - 90x^2 + 18x^3 - x}{6}
\end{aligned}
$$

The light intensity, $I_{p,l}$, projected onto the detector array is defined as [6][8]:

$$I_{p,l} = E \bullet E^*$$

resulting in:

$$I_{p,l}(r,\theta) = \frac{|E_0|^2}{w^2(z)}\left(\frac{2r^2}{w^2(z)}\right)^l \left[L_p^{(l)}\left(\frac{2r^2}{w^2(z)}\right)\right]^2 \cos^2 l\theta \exp\left[\frac{-2r^2}{w^2(z)}\right]$$

Polar coordinates can be replaced with $r^2 = x^2 + y^2$ and $\theta = \arctan\left[\frac{y}{x}\right]$ to represent rectangular coordinates. The first 64 Laguerre mode intensity patterns are shown in Figures 7 and 8. Tables 5, 6, 7, and 8 contain intensity patterns with 64 gray levels. These mode tables assist the User in the mode creation and correlation process.

The Hermite and Laguerre Gaussian beam modes data files are calculated using sixty-fourth increments over a two inch square area. The sixty-fourth increments produce a 128 by 128 data file. Each simulated detector pixel contains 4 by 4 data points that are averaged together to represent the energy projected on that pixel. The detector pixel gap spacing size is 1/5 of each data point and only 1/20 of a pixel element width. Therefore, the gap spacing is neglected for this simulation.

A new file is created by using the values in the "START.DAT" file, beam type, and mode type. The User can define the rotation (clockwise) of a Hermite or Laguerre mode in the "STARTUP.DAT".

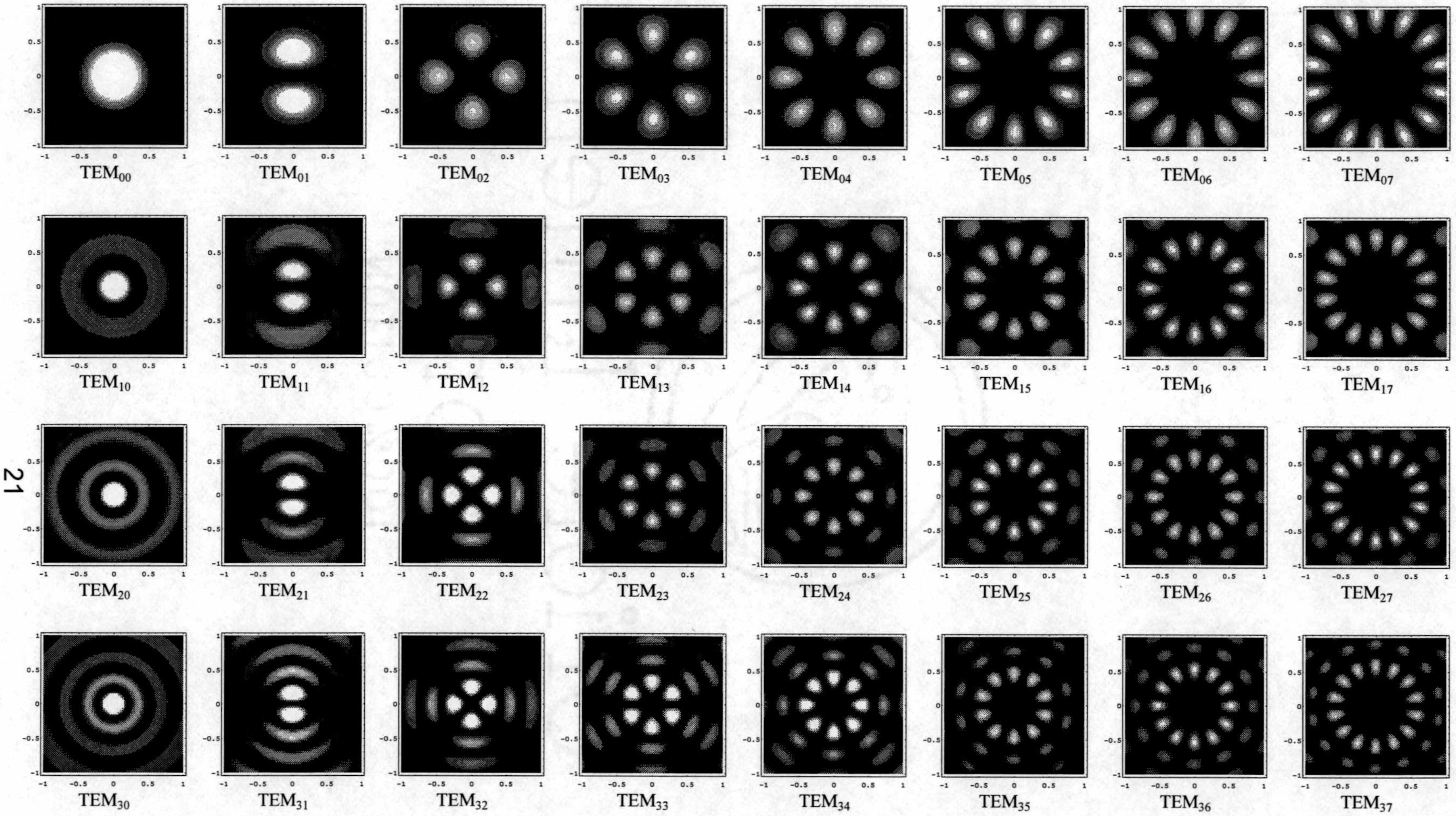


Figure 7. Laguerre-Gaussian Modes (Beam Waist Equals 1 Inch).

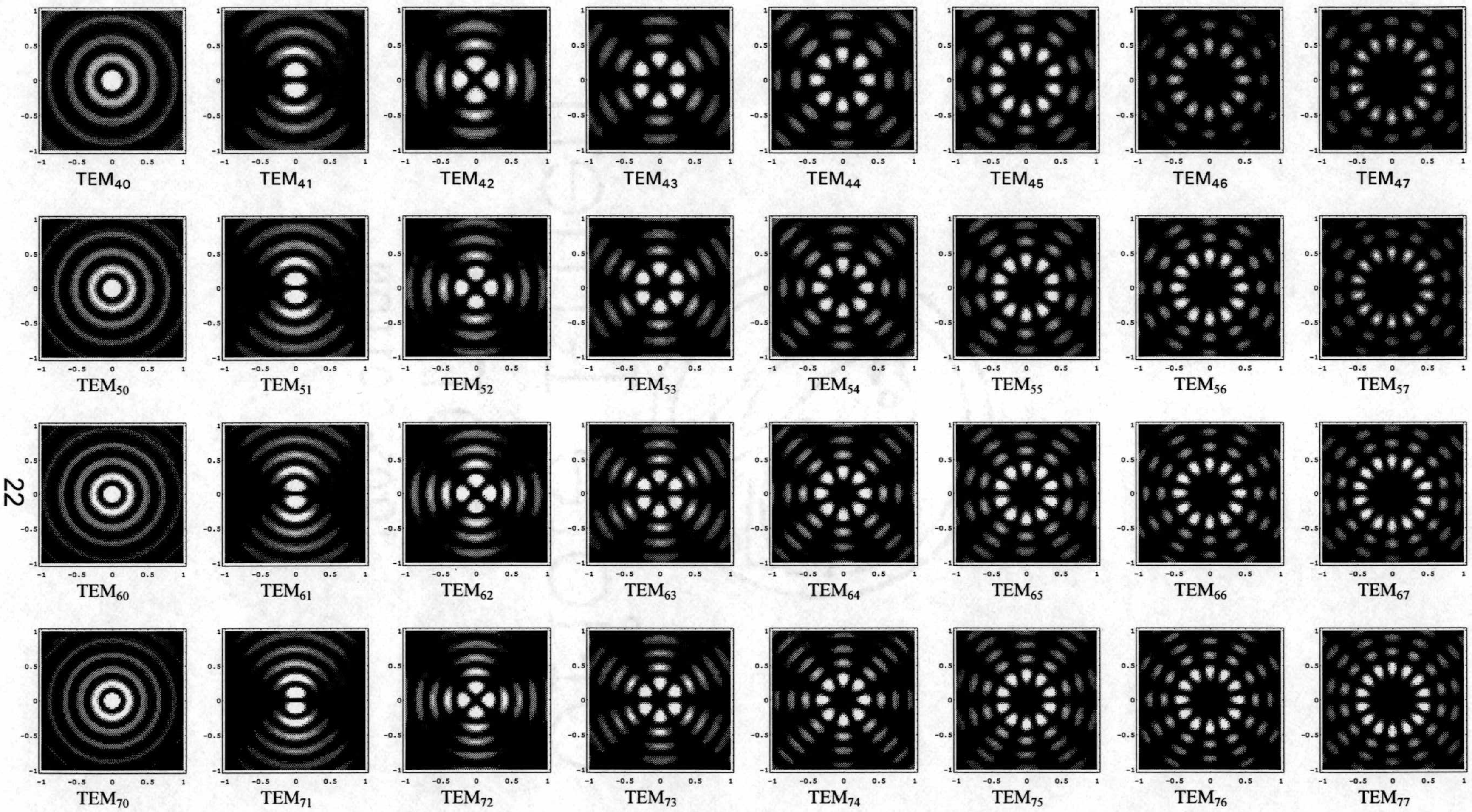


Figure 8. Laguerre-Gaussian Modes Continued (Beam Waist Equals 1 Inch).

The x and y increments are processed in a rotational matrix as shown in the following [9]:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

results in:

$$x' = (\cos\theta)x - (\sin\theta)y$$

$$y' = (\sin\theta)x + (\cos\theta)y$$

where θ is in radians.

The new 128 by 128 data file array in a raw data format is denoted as "filename.BIG" and is stored to the computer's hard drive to be used in future processing. The raw data is further normalized by the maximum value in the file. The normalization enables the program to plot values from 0 to 1. The new normalized file, denoted as "filename.NOR", is reduced to a 32 by 32 data array by averaging 4 by 4 data array elements over the energy projected onto the surface area of that detector. The 32 by 32 data array file is denoted as "filename.ary". Both the normalized file, "filename.NOR", and reduced file, "filename.ary", are used during the fourth option, "Plot Array". After the new files are created, the program returns the User back to the Main Menu. The "Create Array" subroutine structure is shown in Figure 9.

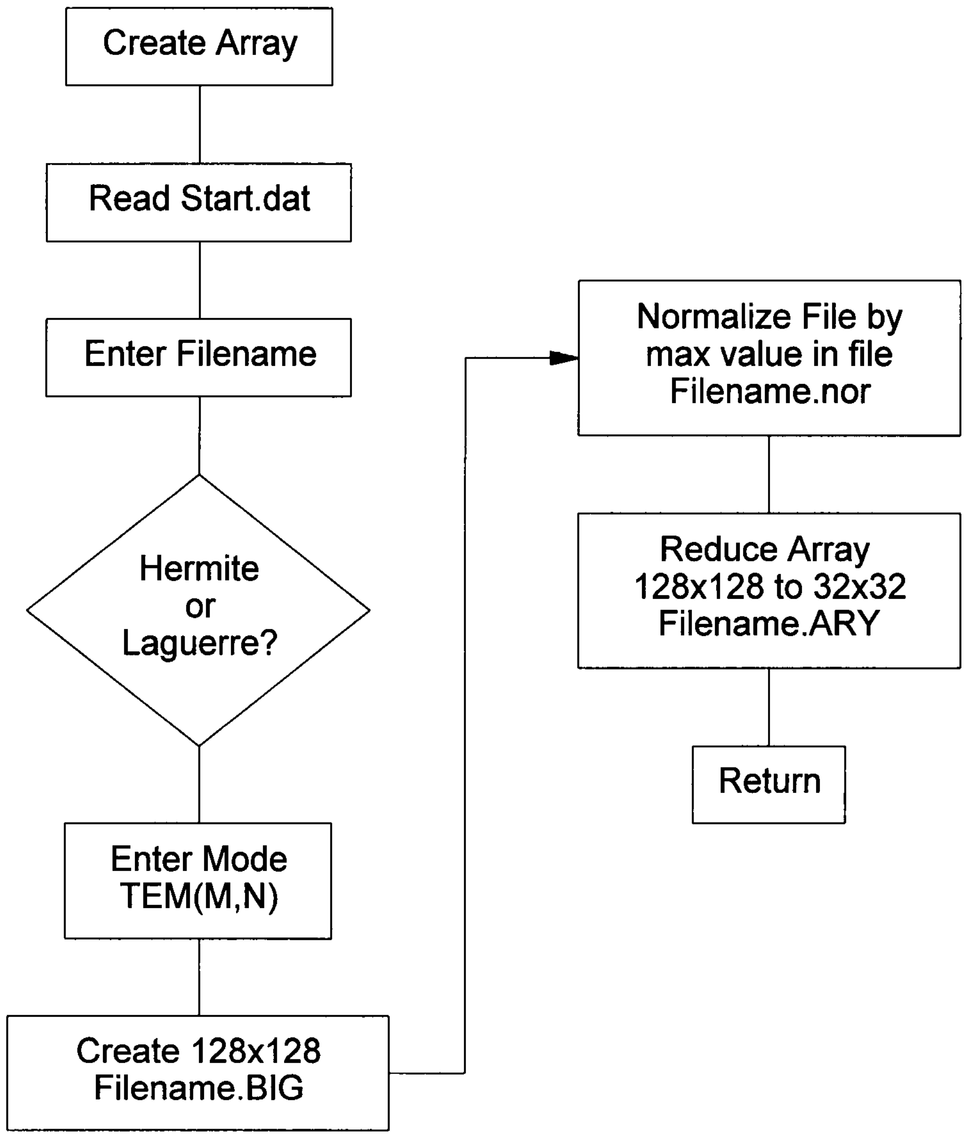


Figure 9. Create Array Subroutine Structure.

A summary of the files created are listed in Table 2.

Table 2. Program File Notation

File Name	Purpose
Modes.exe	Main program
Start.dat	Contains angular position, beam waist size, and Z-position (distance from beam waist) used for startup data in creating mode files.
*.big	A single mode file created 128 x128.
*.nor	Normalized *.big and/or *.mod file used for 128 x128 plots and reduction to *.ary file .
*.ary	Mode file reduced in size from *.nor 128x128 file to a 32 x 32 file. Used for 32 x 32 array plot.
*.mod	A mixed mode file using percentages of other modes. 128 x 128 data size.
*.nos	Mode file with Gaussian noise added. This file is created and used during the correlation process comparing to a reference file.

PLOTTING ARRAYS

Option four plots an existing data file. The computer monitor is set at a 640 by 480 pixel resolution with 16 colors screen mode during the menu screens, but is changed to a 300 by 200 pixel resolution with 256 colors screen mode when the program begins to plot. The screen change was necessary to allow the User to visualize the plotted modes and to reduce the computer hardware requirements. Option four, "Plot Arrays", provides a directory of all existing normalized, "*.NOR", files on the hard drive available to plot. The User enters the filename and chooses between 1 for black-and-white or 2 for color display. Both options use 64 shades where each shade represents one sixty-fourth (1/64) value of an intensity range from 0 to 1. The routine draws a large box, from the left side to the middle of the screen, containing 32 by 32 outlined smaller boxes simulating the detector array. The smaller boxes are filled with a shade that corresponds to a value in the "filename.ARY" file. The plot allows the User to view an averaged pixel output of a 32 by 32 detector array. Another box is drawn, from the right side to the middle of the screen, where "filename.NOR" is plotted to represent a Gaussian beam image before the detector has averaged the areas. Both plots are displayed to aid the User in determining the Gaussian beam mode structures. A scale bar is also displayed at the bottom of the screen for identification of the intensity level. The plot routine requires approximately 2 minutes to plot on a 386DX-20 MHz computer, whereas a 90 MHz Pentium can plot the files in less than 5 seconds. After the plot has been completed, the program returns to the User back to the Main Menu. The plot array subroutine structure is shown in Figure 10. Some examples of the visual plot on the computer display are shown in Figure 11. The User will use these visual plots to aid in the preliminary mode identification. Notice, as the higher modes are plotted, the 32x32 array has a lower resolution thus making the visual mode identification process more complicated.

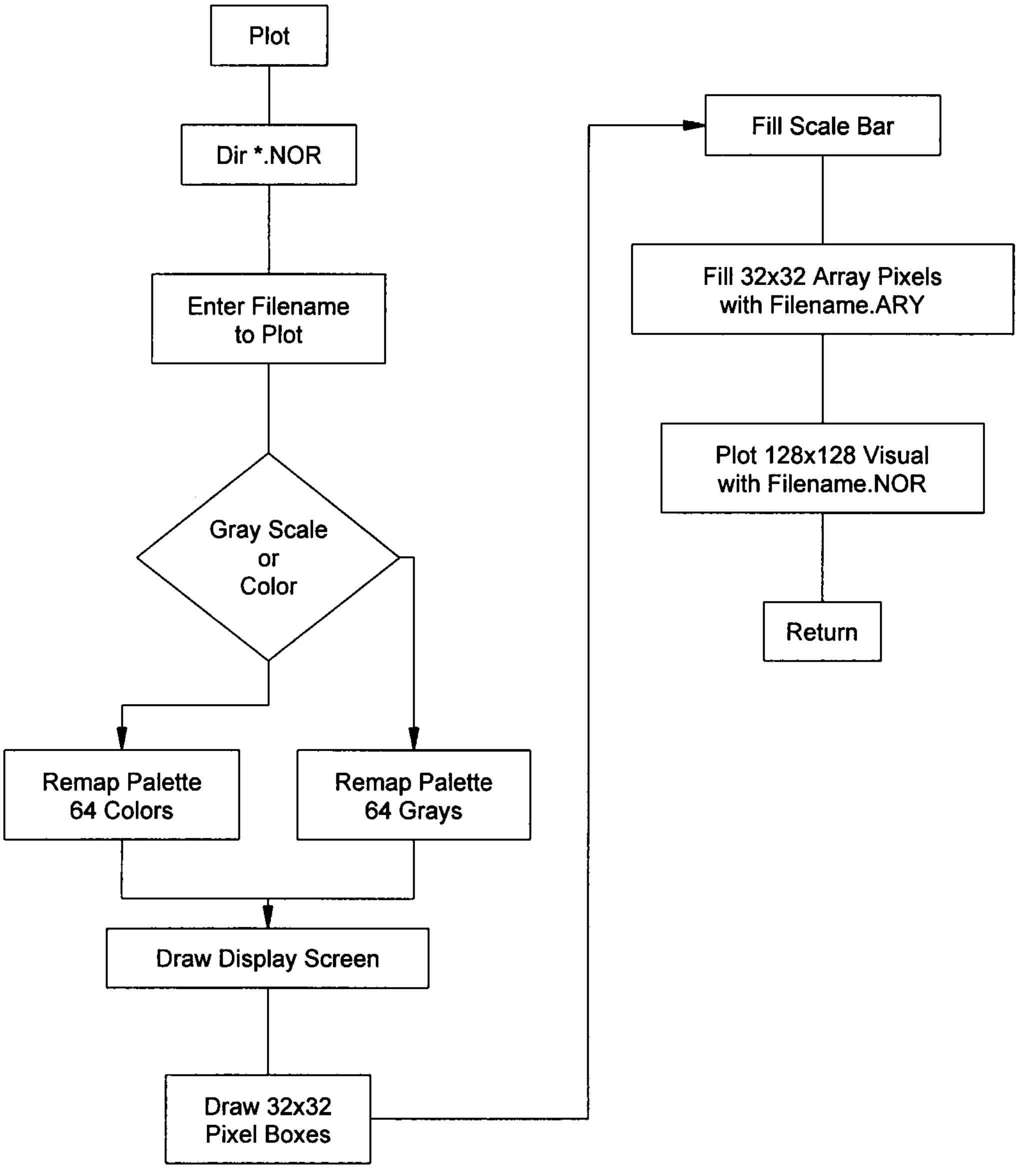
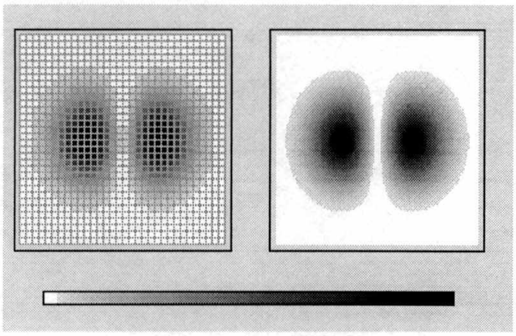
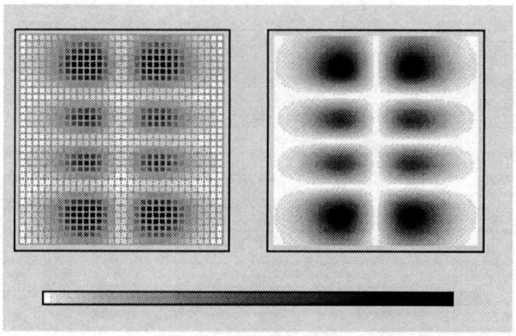


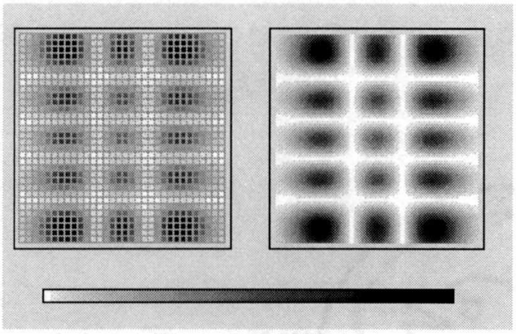
Figure 10. Plot Array Subroutine Structure



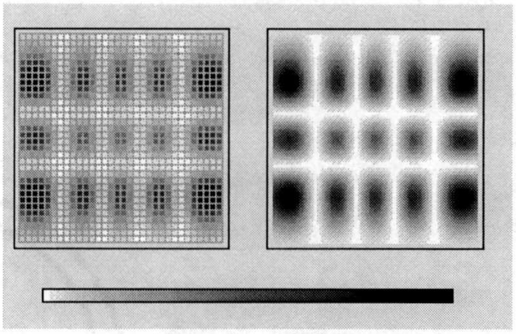
Hermite $TEM_{(1,0)}$



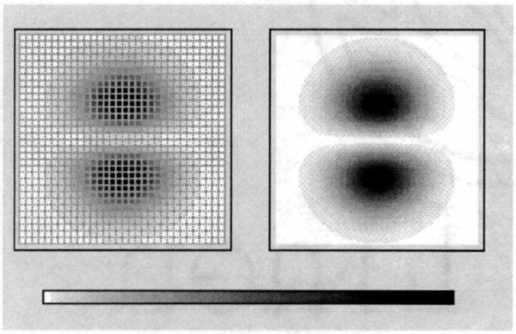
Hermite $TEM_{(1,3)}$



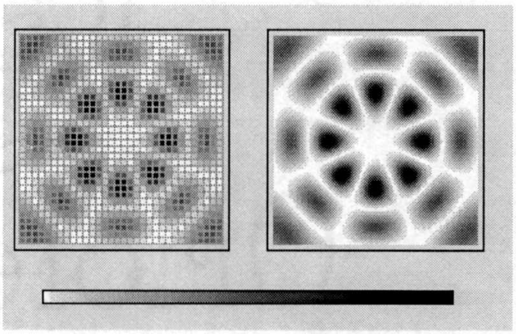
Hermite $TEM_{(2,4)}$



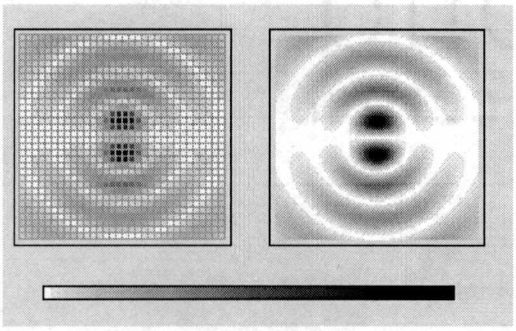
Hermite $TEM_{(4,2)}$



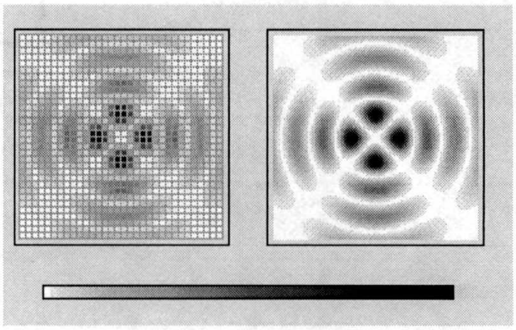
Laguerre $TEM_{(0,1)}$



Laguerre $TEM_{(2,4)}$



Laguerre $TEM_{(3,1)}$



Laguerre $TEM_{(4,2)}$

Figure 11. Computer Display - Visual Plots

MIXING ARRAYS

In option five, "Mixing Arrays", the User can mix existing Gaussian beam mode files. The program prompts the User to enter the number of files to mix. After the filenames are entered, the User is prompted for the files amplitude percentage. The total file percentages can not exceed one hundred percent (100%). If so, the process has to be repeated. As an example, the User can specify 50% of a Hermite $TEM_{(0,0)}$ mode to be mixed with a 50% Laguerre $TEM_{(2,3)}$ mode. Any number of combinations of mode mixing can be processed just as long as the total percentages add up to 100% and the "filename.BIG" files exist. These files are amplitude distribution mixed with real, positive weightings. The software program does not have the provision for varying different phases (complex weighting factors).

After the User provides the files to be mixed, each "filename.BIG" is opened and multiplied by the User defined percentage. The file is further added to a temporarily 128 by 128 memory matrix, later labeled as "filename.MOD". The mixed file is then normalized and reduced to a 32 by 32 data file, "filename.NOR" and "filename.ARY", respectively. The program returns to the Main Menu. The mixing array subroutine structure is shown in Figure 12.

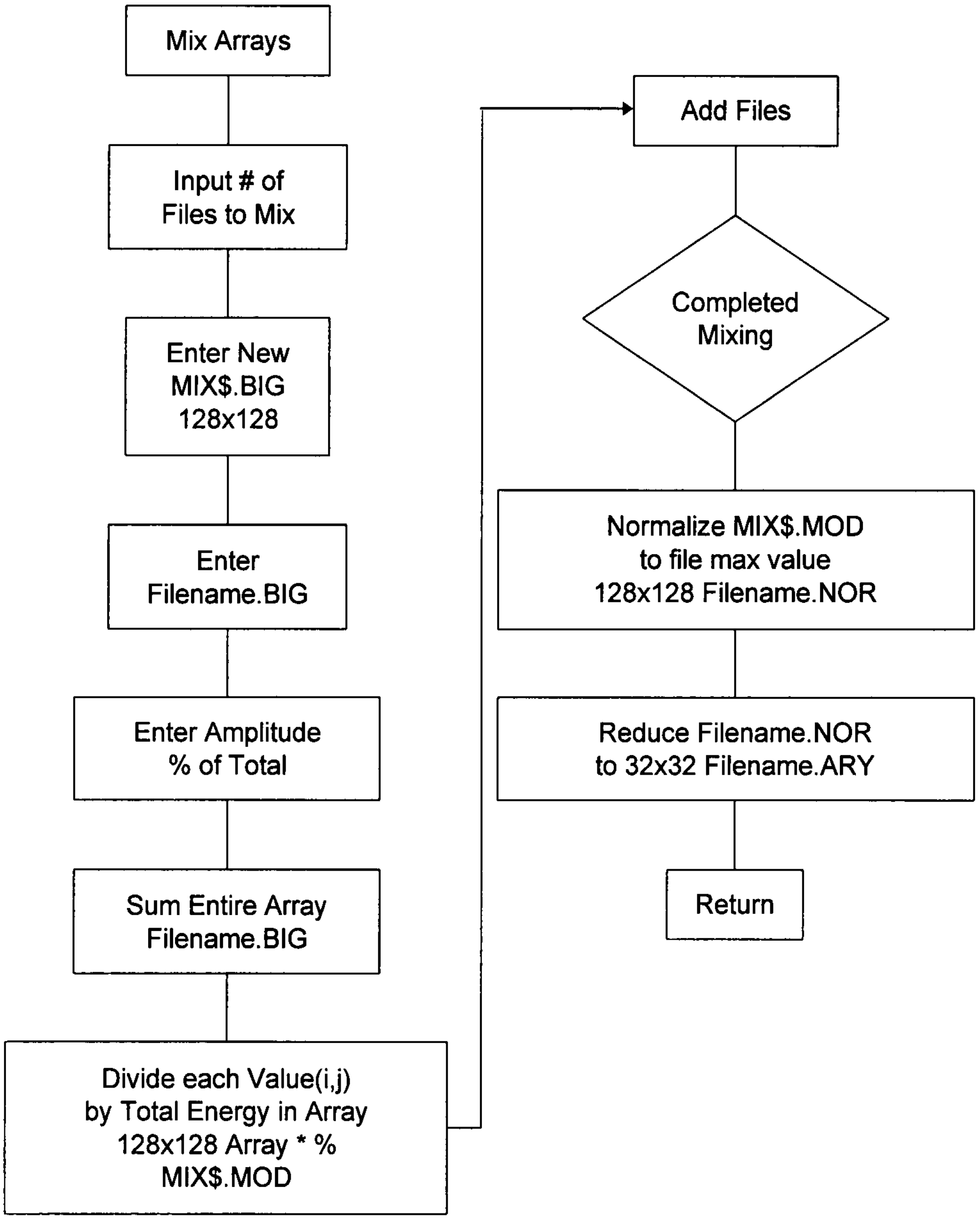


Figure 12. Mixing Array Subroutine Structure

CORRELATION PROCESS

In option six, "Correlation Process", the User can cross-correlate the data in any two existing 32 by 32 detector array files. These files, denoted as the reference and test sets, can be the same or different Gaussian beam mode files. The reference set is an existing file specified by the User, "filename.ary". The test set is an existing file specified by the User, "filename.ary", that has Gaussian noise added to each 32 by 32 data array and is saved as "filename.nos". The unit variance Gaussian noise probability density function is defined as [11]:

$$p(n) = \frac{1}{\sqrt{2\pi}} e^{-n^2/2}$$

Random numbers following this probability density function can be generated by using the following transformation equations:

$$n_1 = \sqrt{-2 \ln u_1} \cos 2\pi u_2$$

$$n_2 = \sqrt{-2 \ln u_1} \sin 2\pi u_2$$

where u_1, u_2 are random numbers uniformly distributed on (0,1). A 32 by 32 array of unit-variance Gaussian noise $n(x, y)$ at discrete positions (x, y) is generated using these transformation equations. A noisy test intensity distribution $I_t(x, y)$ is then formed from an ideal reference intensity $I_r(x, y)$ by:

$$I_t(x,\ y) \;=\; I_r(x,\ y)\left[1 \;+\; \sigma n(x,\ y)\right]$$

The standard deviation provides an error bands on the amount of noise added based upon the intensity of the mode at a particular (x, y) position.

The purpose of the cross-correlation is to measure the similarity of a reference file to test file. The cross-correlation of two discrete 32 by 32 arrays in defined as [11]:

$$\Re_{rt}(s, q) = \sum_{m=1}^{32} \sum_{n=1}^{32} I_t(x_m, y_n) I_r(x_m + s, y_m + q)$$

where I_t is the test intensity file and I_r is the reference intensity file. Note that the cross-correlation can be calculated for any test and reference arrays, not just the original and noise-corrupted versions as given above. For this study, the test and reference files coordinate origin were all coincident. Therefore, terms s and q represent a lag and were set to $s = q = 0$. The cross-correlation function can be normalized by dividing by the square root of the sum of the squares for each test and reference intensity files. The normalization process produces a cross-correlation coefficient ρ_{r-t}, with values ranging from 0 to 1 [11]. A cross-correlation coefficient of 1.0 indicates an identical match. ρ_{r-t} is defined by:

$$\rho_{r-t} = \frac{\sum_{m=1}^{32}\sum_{n=1}^{32} I_t(x_m, y_n) I_r(x_m, y_n)}{\sqrt{\sum_m \sum_n I_t^2(x_m, y_n)}\sqrt{\sum_m \sum_n I_r^2(x_m, y_n)}}$$

The correlation process subroutine structure is shown in Figure 13.

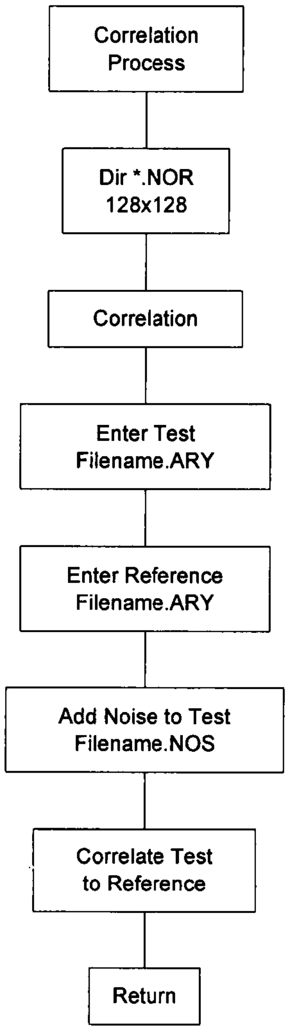


Figure 13. Correlation Process Subroutine Structure

CHAPTER IV

RESULTS

Several cross-correlation data runs were performed comparing reference files to test files with random Gaussian noise added. Several data runs involved the comparison of low-order Hermite Gaussian modes with other low-order Hermite Gaussian modes, low-order Laguerre Gaussian modes with other low-order Laguerre Gaussian modes, and Hermite Gaussian modes with Laguerre Gaussian modes. And finally, some mixed modes with a combination of Hermite and Laguerre Gaussian modes were compared with individual modes and other mixed modes. Each mode correlated with an identical mode with noise added are highlighted on the correlation data tables.

Table 3 represents the correlation data using a standard deviation, σ , equal to zero which compares the reference files with noise-free test files. The results show that all of the beam patterns with matching mode structures had a correlation of 1.0, meaning exact match. Also, all of the reference files compared to mixed mode patterns with a large component of the main mode had a high (>0.8) correlation coefficient. All reference files compared to other beam patterns had correlation coefficients ranging from 0.31 to 0.70. The case with $\sigma = 0.0$ shows high degree of confidence in

Table 3. Correlation Data - Standard Deviation $\sigma = 0.0$

	Test Files with No Noise Standard Deviation = 0.0								
	L0001	L0010	L0011	L0012	L0013	H0001	H0011	MIX1	MIX2
Reference Files									
L0001	1	0.417	0.638	0.487	0.47	1	0.581	**0.874**	**0.905**
L0010	0.417	1	0.528	0.306	0.291	0.417	0.477	**0.806**	0.517
L0011	0.639	0.528	1	0.533	0.332	0.639	0.373	0.698	0.639
L0012	0.487	0.306	0.533	1	0.557	0.487	0.218	0.481	0.518
L0013	0.47	0.291	0.332	0.558	1	0.47	0.486	0.471	0.601
L0021	0.593	0.564	0.727	0.38	0.411	0.593	0.345	0.688	0.575
L0022	0.521	0.409	0.577	0.719	0.363	0.52	0.223	0.558	0.529
L0031	0.608	0.619	0.714	0.383	0.343	0.608	0.353	0.727	0.585
H0001	1	0.417	0.639	0.487	0.47	1	0.581	**0.874**	**0.905**
H0010	0.337	0.417	0.217	0.487	0.47	0.337	0.581	0.443	0.407
H0011	0.581	0.477	0.373	0.218	0.486	0.581	1	0.634	0.7
H0012	0.371	0.516	0.485	0.361	0.249	0.371	0.638	0.517	0.447
H0013	0.308	0.379	0.588	0.361	0.407	0.308	0.531	0.404	0.371
H0021	0.471	0.516	0.449	0.361	0.554	0.471	0.638	0.583	**0.76**
MIX1 L0001*.5 L0010*.5	**0.874**	**0.805**	0.698	0.48	0.462	**0.874**	0.634	1	**0.866**
MIX 2 L0001*.5 H0021*.25 H0031*.25	**0.905**	0.517	0.639	0.518	601	**0.906**	0.7	**0.867**	1

identifying the major low-order mode in a mixed mode beam pattern with correlation coefficients above 0.80. However, the $\sigma = 0.0$ is an ideal condition and is not believed to be a true comparison representation.

Table 4 presents the correlation data using a $\sigma = 0.1$ which compares the reference files with noisy test files. The results show that all of the files with the same mode structure had correlation coefficients ranging between 0.80 to 0.97. All reference files compared to test files with different mode structures had correlation coefficients ranging from 0.31 to 0.73. The case with $\sigma = 0.1$ again shows a high degree of confidence in identifying with correlation coefficients above 0.80. The standard deviation used is believed to be more representative of the laser beam patterns on the array in practice. However, the true representation of the noise will be dependent upon the test setup (hardware) and the operating environment.

Table 5 represents the correlation data using a $\sigma = 0.3$. The results show that all of the files with the same mode structure had a correlation coefficients ranging between 0.72 to 0.89. All reference files compared to test files with different mode structures had correlation coefficients ranging from 0.37 to 0.68. The case with $\sigma = 0.3$ seems to be where the confidence in using the detector array to identify even the dominant mode in a beam pattern breaks down. The standard deviation utilized could be excessive.

Table 6 represents the correlation data using a $\sigma = 0.5$. The results

Table 4. Correlation Data - Standard Deviation σ = 0.1

	Test Files with Gaussian Noise Standard Deviation = 0.1								
	L0001	L0010	L0011	L0012	L0013	H0001	H0011	MIX1	MIX2
Reference Files									
L0001	**0.96**	0.469	0.639	0.526	0.506	**0.953**	0.596	**0.833**	**0.863**
L0010	0.493	**0.923**	0.589	0.391	0.382	0.496	0.537	**0.801**	0.562
L0011	0.686	0.578	**0.948**	0.582	0.41	0.686	0.45	0.717	0.666
L0012	0.568	0.444	0.594	**0.966**	0.598	0.569	0.326	0.541	0.571
L0013	0.552	0.45	0.464	0.607	**0.974**	0.562	0.559	0.528	0.638
L0021	0.656	0.614	0.735	0.462	0.47	0.648	0.43	0.707	0.611
L0022	0.574	0.491	0.612	0.722	0.419	0.583	0.318	0.586	0.561
L0031	0.654	0.634	0.729	0.457	0.407	0.649	0.425	0.726	0.615
H0001	**0.955**	0.473	0.641	0.514	0.496	**0.957**	0.593	**0.834**	**0.857**
H0010	0.405	0.47	0.311	0.528	0.498	0.416	0.607	0.485	0.451
H0011	0.632	0.55	0.453	0.317	0.535	0.63	**0.968**	0.65	0.703
H0012	0.472	0.597	0.551	0.455	0.343	0.48	0.674	0.563	0.509
H0013	0.423	0.495	0.634	0.447	0.478	0.421	0.595	0.481	0.439
H0021	0.557	0.594	0.529	0.446	0.594	0.552	0.674	0.614	**0.764**
MIX1 L0001*.5 L0010*.5	**0.894**	**0.799**	0.729	0.55	0.525	**0.891**	0.679	**0.969**	**0.86**
MIX 2 L0001*.5 H0021*.25 H0031*.25	**0.922**	0.602	0.685	0.582	0.65	**0.92**	0.735	**0.865**	**0.972**

Table 5. Correlation Data - Standard Deviation $\sigma = 0.3$

	Test Files with Gaussian Noise Standard Deviation = 0.3								
	L0001	L0010	L0011	L0012	L0013	H0001	H0011	MIX1	MIX2
Reference Files									
L0001	**0.806**	0.489	0.574	0.504	0.504	**0.809**	0.576	**0.721**	**0.737**
L0010	0.566	**0.803**	0.602	0.476	0.447	0.548	0.563	**0.734**	0.573
L0011	0.675	0.6	**0.818**	0.589	0.484	0.678	0.516	0.693	0.633
L0012	0.598	0.509	0.608	**0.859**	0.612	0.589	0.432	0.577	0.59
L0013	0.619	0.533	0.528	0.629	**0.883**	0.618	0.594	0.566	0.638
L0021	0.663	0.603	0.687	0.512	0.538	0.655	0.512	0.677	0.618
L0022	0.585	0.517	0.583	0.683	0.468	0.571	0.406	0.571	0.559
L0031	0.634	0.583	0.658	0.501	0.46	0.627	0.489	0.681	0.599
H0001	**0.808**	0.461	0.572	0.492	0.501	**0.812**	0.587	**0.726**	**0.753**
H0010	0.434	0.475	0.368	0.509	0.503	0.446	0.577	0.48	0.455
H0011	0.606	0.526	0.495	0.416	0.538	0.614	**0.86**	0.623	0.668
H0012	0.535	0.573	0.559	0.499	0.42	0.528	0.675	0.583	0.544
H0013	0.507	0.522	0.627	0.499	0.527	0.512	0.613	0.523	0.514
H0021	0.583	0.568	0.558	0.493	0.601	0.587	0.665	0.638	**0.734**
MIX1 L0001*.5 L0010*.5	**0.83**	**0.729**	0.679	0.592	0.551	**0.823**	0.668	**0.87**	**0.801**
MIX 2 L0001*.5 H0021*.25 H0031*.25	**0.846**	0.584	0.668	0.619	0.659	**0.85**	0.69	**0.808**	**0.885**

Table 6. Correlation Data - Standard Deviation $\sigma = 0.5$

	Test Files with Gaussian Noise Standard Deviation = 0.5								
	L0001	L0010	L0011	L0012	L0013	H0001	H0011	MIX1	MIX2
Reference Files									
L0001	**0.732**	0.478	0.554	0.507	0.501	**0.732**	0.558	**0.693**	**0.697**
L0010	0.567	**0.698**	0.57	0.499	0.483	0.566	0.564	**0.723**	0.569
L0011	0.641	0.572	**0.764**	0.591	0.495	0.658	0.52	0.667	0.637
L0012	0.601	0.541	0.599	**0.798**	0.611	0.607	0.474	0.581	0.601
L0013	0.596	0.531	0.556	0.637	**0.836**	0.61	0.626	0.594	0.653
L0021	0.647	0.579	0.673	0.527	0.545	0.639	0.525	0.661	0.601
L0022	0.561	0.518	0.579	0.637	0.487	0.573	0.438	0.562	0.557
L0031	0.635	0.586	0.623	0.498	0.473	0.629	0.496	0.655	0.567
H0001	**0.736**	0.457	0.551	0.504	0.504	**0.741**	0.557	**0.675**	**0.703**
H0010	0.451	0.457	0.385	0.504	0.505	0.437	0.552	0.489	0.463
H0011	0.599	0.527	0.478	0.449	0.551	0.605	**0.808**	0.623	0.639
H0012	0.529	0.568	0.572	0.506	0.466	0.54	0.666	0.587	0.563
H0013	0.523	0.558	0.636	0.535	0.547	0.532	0.621	0.545	0.543
H0021	0.587	0.568	0.563	0.519	0.605	0.585	0.652	0.62	**0.7**
MIX1 **L0001*.5** **L0010*.5**	**0.782**	**0.692**	0.657	0.58	0.569	**0.765**	0.673	**0.806**	**0.768**
MIX 2 **L0001*.5** **H0021*.25** **H0031*.25**	**0.809**	0.604	0.676	0.618	0.642	**0.805**	0.709	**0.763**	**0.841**

show that all correlations did not provide a distinct correlation between matched and unmatched modes. The $\sigma = 0.5$ case is an extreme case where the noise level is excessive and would preclude the use of this device.

For low-noise data ($\sigma = 0.0$ and $\sigma = 0.1$), correlations between individual modes with themselves provided an acceptable cross-correlation coefficient. Correlations between different modes had a low correlation coefficient, as expected. A correlation between a single mode and a mixed mode had a high correlation coefficient only if the single mode was the dominant mode in the mixed mode file. As a general trend, the ability to identify beam modes with confidence became harder to distinguish as more noise was added to the reference file. The limit appeared to be around and beyond $\sigma = 0.3$.

The software program includes a rotation aspect that allows the User to rotate a Hermite or Laguerre Gaussian beam on the detector array. The option allows a User to view modes at different orientations and identify laser modes at a later date. A limited few data runs were made to check the rotation aspects of this program. The program easily allows a visual display of a Hermite or Laguerre Gaussian beam on the 32 by 32 detector array, however, the cross-correlation for a Hermite $TEM_{(0,1)}$ compared to a rotated Hermite $TEM_{(0,1)}$ failed. The rotation angle was set to 5, 10, 15 and 45 degrees. All cross-correlation coefficients were below 0.6 indicating unsuccessful matches.

CHAPTER V

CONCLUSION

In conclusion, a software program was written to determine if a 32 by 32 detector array could distinguish the structure of a high-order TEM mixed Gaussian beam modes. The program allows the User to create Laguerre and Hermite Gaussian beam modes or mixed Laguerre and Hermite Gaussian beam modes with the capability to change the beam size, non-complex amplitude, and rotation aspects. The program also allows the User to display the generated file on a simulated 32 by 32 detector array in black and white or color shades. The program compares single or mixed Gaussian beam modes (reference set) to single or mixed Gaussian beam modes with added Gaussian noise (test sets). A correlation between the reference set and various test sets were performed as a method of identification. All data runs with a standard deviation $\sigma = 0.1$ showed a mode match with correlation coefficient greater than 0.80. All data runs with a standard deviation $\sigma = 0.3$ showed a mode match with correlation coefficients greater than 0.72. Single and mixed mode comparisons were based on equal rotation angles to the reference and test sets.

The results of this study as listed in Chapter IV Tables 3, 4, and 5 demonstrate that mode identification by means of software generated files with a cross-correlation process is feasible to determine the dominant operating mode of a laser beam. However, before a detector is purchased, further study of the laser noise and detector noise should be investigated. And, a further study should identify the properties a beam splitter, chopper and attenuator may contribute to the laser mode detection.

More study is also recommended to determine if a 64 by 64 or a 128 by 128 detector array can provide better results or resolution during the visual identification process. The software program written for this research can be modified to accommodate further investigation of the above mentioned arrays.

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BIBLIOGRAPHY

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APPENDIX

SOFTWARE PROGRAM

```
REM PROGRAM NAME UT3.BAS
REM This program 12-4-95.
REM THE HERMITE AND LAGUARRE IS COMPLETE.  2'''IS PROB.
REM THE MODE MIXING ARE COMPLETE. THE 320X200 SCREEN IS IN
AFFECT.
REM PROGRAM HAS BOTH THE 64 GRAY SCALE AND 64 COLORS.
REM PHASE ANGLES ARE ADDED TO EQUATIONS.
REM ADDED STARTUP.DAT FILE FOR DEFAULTS
REM Adds gauss noise to file using standard deviation 0 to .5 increments .1
REM modification ****changed the gray scale palatte to color palette.
REM
*******************************************************
REM  * This program calculates the Intensity of a Gaussian-Laguerre Laser *
REM  * Mode and creates an array of the profile. 3-12-92             *
REM
**********************************************************
REM
DEFSNG A-Z
MAXDIM = 128    'CONST
DIM PIXEL(-2 TO 2)
DIM NVAL(520), VALUE(520), VAL10(50), VAL20(50), VAL30(50),
VAL40(50)
DIM VAL11(50), VAL21(50), VAL31(50), VAL41(50), VAL12(50),
VAL22(50)
DIM VAL32(50), VAL42(50), VAL14(50), VAL24(50), VAL34(50),
VAL44(50)
DIM TOTALVAL(50), FIRTVAL(50), SECTVAL(50), THRTVAL(50),
FTHTVAL(50), EXTRA(150)
DIM MIXED(1 TO MAXDIM, 1 TO MAXDIM), SUM(1 TO MAXDIM, 1 TO
MAXDIM), MODE(1 TO MAXDIM, 1 TO MAXDIM)
MAIN:
CLS
SCREEN 12
COLOR 15                      '14 YELLOW     15 WHITE
PALETTE 0, 4128768                  'REMAPS THE BACKGROUND TO
CYAN
PRINT
PRINT "
******************************************************"
PRINT "    *       This program creates and plots Gaussian-Laguerre and
*"
```

```
PRINT "    *     Gaussian-Hermite intensity profiles on a 32x32 Pixel Array
*"
PRINT "
********************************************************"
PRINT
PRINT "
********************************************************"
PRINT "         *                    Main Menu                   *"
PRINT "
********************************************************"
PRINT "         *                                            *"
PRINT "         *                                            *"
PRINT "         *              1) List Existing Arrays          *"
PRINT "         *                                            *"
PRINT "         *              2) Change Setup File              *"
PRINT "         *                                            *"
PRINT "         *              3) Create Array                 *"
PRINT "         *                                            *"
PRINT "         *              4) Plot Array                  *"
PRINT "         *                                            *"
PRINT "         *              5) Mix Existing Arrays            *"
PRINT "         *                                            *"
PRINT "         *              6) Correlation Process           *"
PRINT "         *                                            *"
PRINT "         *              7) Quit                      *"
PRINT "         *                                            *"
PRINT "         *            Choose one of the following.           *"
PRINT "         *                                            *"
PRINT "
**********************************************************"
PRINT
INPUT ans1
IF ans1 = 1 GOTO DIR
IF ans1 = 2 GOTO SETUP
IF ans1 = 3 GOTO array
IF ans1 = 4 GOTO plot
IF ans1 = 5 GOTO MIX
IF ans1 = 6 GOTO CORR
IF ans1 = 7 GOTO 1000
DIR:
CLS
PRINT
PRINT
PRINT "Existing Arrays "
```

```
PRINT
SHELL "dir *.ARY /B"
PRINT
PRINT
      PRINT "Press space bar to continue"
      DO
      LOOP WHILE INKEY$ = ""
GOTO MAIN
SETUP:
CLS
OPEN "STARTUP.DAT" FOR INPUT AS #1
INPUT #1, RAMPLITUDE, Wz, theta
PRINT
PRINT
PRINT "            THE CURRENT DEFAULT VALUES ARE:"
PRINT
PRINT "   AMPLITUDE", RAMPLITUDE; "   WAIST", Wz; "     PHASE
ANGLE", theta
PRINT
CLOSE #1
PRINT
PRINT
PRINT "  WOULD YOU LIKE TO CHANGE THE SETUP FILE? "
INPUT "  (1 = YES  2 = NO)", ANS3
IF ANS3 = 1 THEN
      OPEN "STARTUP.DAT" FOR OUTPUT AS #2
      PRINT
      PRINT
      PRINT
      INPUT "         THE NEW AMPLITUDE IS: ", RAMPLITUDE
      PRINT
      INPUT "         THE NEW WAIST DISTANCE IS: ", Wz
      PRINT
      INPUT "         THE NEW PHASE ANGLE IS: ", theta
      WRITE #2, RAMPLITUDE, Wz, theta
      CLOSE #2
ELSEIF ANS3 = 2 THEN
      PRINT "THANKYOU"
END IF
GOTO MAIN
array:
CLS
REM *** The Array is created by starting with X-Y in top left corner.
REM *** Completing all of X with Y constant and then incrementing down
```

```
REM *** until X-Y lower Right corner is calculated.
REM
REM *** The array size is considered a 2 inch by 2 inch array.
REM *** There is 128 x 128 data points taken.
REM *** stnum should be set to .015748 to provide at least a 2"x 2" data
selection
REM *** for a 128x128 array.  It is currently setup for a 128x128 data
selection.
MODE:
OPEN "STARTUP.DAT" FOR INPUT AS #5
INPUT #5, RAMPLITUDE, Wz, theta
CLOSE #5
pi = 3.141593
angle = theta * (pi / 180)
PRINT ""
PRINT " "
PRINT "                    PLEASE ENTER THE TYPE OF GAUSSIAN BEAM"
INPUT "           1:= GAUSSIAN-HERMITE BEAM    2 := GAUSSIAN-
LAGUERRE"; BTYPE
      IF BTYPE < 1 OR BTYPE > 2 THEN
            CLS
            PRINT
            PRINT
            PRINT "          YOUR CHOICES ARE  ( 1 OR 2 )"
            PRINT "          PLEASE TRY AGAIN"
            GOTO MODE
      END IF
PRINT " "
PRINT " "
PRINT " "
INPUT "        WHAT IS The Array NAME to create? ", array$
PRINT "    "
PRINT "    "
CLOSE #2
DATAOUT$ = array$ + ".BIG"
OPEN DATAOUT$ FOR OUTPUT AS #2
IF BTYPE = 1 THEN
      PRINT "        ENTER MODE:   TEM (m,n)    "
            INPUT "        m = ", m
            INPUT "        n = ", n
            IF m < 0 OR m > 7 THEN
                  PRINT "        Try again - 0 to 7."
                  GOTO MODE
            ELSEIF n < 0 OR n > 7 THEN
```

```
                PRINT "        Try again - 0 to 7."
                GOTO MODE
           END IF
       GOTO HERMITE
ELSEIF BTYPE = 2 THEN
       PRINT "        ENTER MODE   TEM (p,l):  "
           INPUT "         p = ", p
           INPUT "         l = ", L
       IF p < 0 OR p > 7 THEN
                PRINT "        Try again - 0 to 7."
                GOTO MODE
       ELSEIF L < 0 OR L > 7 THEN
                PRINT "        Try again - 0 to 7."
                GOTO MODE
       END IF
       GOTO LAGUERRE
END IF

HERMITE:
MAX = 0
PRINT
PRINT
PRINT "        Calculating"
FOR Y = 1! TO -1! STEP -.015748                '- STNUM!
REM              *** Complete x scan first***
FOR x = -1! TO 1! STEP .015748                 ' STNUM!
xprime = (x * COS(angle)) + (Y * (-1 * SIN(angle)))
yprime = (x * SIN(angle)) + (Y * COS(angle))
REM added phase angle rotation - clockwise
HX = (((2 ^ .5) * xprime) / Wz)
HY = (((2 ^ .5) * yprime) / Wz)
IF m = 0 THEN
           Hm = 1
       ELSEIF m = 1 THEN
           Hm = 2 * HX
       ELSEIF m = 2 THEN
           Hm = 4 * HX ^ 2 - 2
       ELSEIF m = 3 THEN
           Hm = 8 * HX ^ 3 - 12 * HX
       ELSEIF m = 4 THEN
           Hm = 16 * HX ^ 4 - 48 * HX ^ 2 + 12
       ELSEIF m = 5 THEN
           Hm = 32 * HX ^ 5 - 160 * HX ^ 3 + 120 * HX
       ELSEIF m = 6 THEN
```

```
            Hm = 64 * HX ^ 6 - 480 * HX ^ 4 + 720 * HX ^ 2 - 120
        ELSEIF m = 7 THEN
            Hm = 128 * HX ^ 7 - 1344 * HX ^ 5 + 3360 * HX ^ 3 - 1680
* HX
        END IF
IF n = 0 THEN
            Hn = 1
        ELSEIF n = 1 THEN
            Hn = 2 * HY                 'TY
        ELSEIF n = 2 THEN
            Hn = 4 * HY ^ 2 - 2
        ELSEIF n = 3 THEN
            Hn = 8 * HY ^ 3 - 12 * HY
        ELSEIF n = 4 THEN
            Hn = 16 * HY ^ 4 - 48 * HY ^ 2 + 12
        ELSEIF n = 5 THEN
            Hn = 32 * HY ^ 5 - 160 * HY ^ 3 + 120 * HY
        ELSEIF n = 6 THEN
            Hn = 64 * HY ^ 6 - 480 * HY ^ 4 + 720 * HY ^ 2 - 120
        ELSEIF n = 7 THEN
            Hn = 128 * HY ^ 7 - 1344 * HY ^ 5 + 3360 * HY ^ 3 - 1680 *
HY
        END IF
SINTENSITY = ((RAMPLITUDE / Wz) ^ 2) * (Hm ^ 2) * (Hn ^ 2) * EXP((-2 *
(xprime ^ 2 + yprime ^ 2)) / (Wz ^ 2))
PIXEL(x) = SINTENSITY
PRINT #2, PIXEL(x);
IF SINTENSITY > MAX THEN
      MAX = SINTENSITY
      END IF
NEXT x
PRINT #2,
NEXT Y
CLOSE #2
GOTO NORM

REM
LAGUERRE:
REM
REM *** CALCULATING FOR LAGUERRE POLYNOMIALS
MAX = 0
PRINT
PRINT
PRINT "         Calculating"
```

```
FOR Y = 1! TO -1! STEP -.015748                '- STNUM!
REM              *** Complete x scan first***
FOR x = -1! TO 1! STEP .015748                 ' STNUM!
LR = 2 * (x ^ 2 + Y ^ 2) / (Wz ^ 2)

    IF p = 0 THEN              'anytime p=0 then Lp=1, l doesn't matter
        Lp = 1
    ELSEIF p = 1 AND L = 0 THEN
        Lp = 1 - LR
    ELSEIF p = 1 AND L = 1 THEN
        Lp = 2 - LR
    ELSEIF p = 1 AND L = 2 THEN
        Lp = 3 - LR
    ELSEIF p = 1 AND L = 3 THEN
        Lp = 4 - LR
    ELSEIF p = 1 AND L = 4 THEN
        Lp = 5 - LR
    ELSEIF p = 1 AND L = 5 THEN
        Lp = 6 - LR
    ELSEIF p = 1 AND L = 6 THEN
        Lp = 7 - LR
    ELSEIF p = 1 AND L = 7 THEN
        Lp = 8 - LR
    ELSEIF p = 2 AND L = 0 THEN
        Lp = (2 - 4 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 1 THEN
        Lp = (6 - 6 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 2 THEN
        Lp = (12 - 8 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 3 THEN
        Lp = (20 - 10 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 4 THEN
        Lp = (30 - 12 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 5 THEN
        Lp = (42 - 14 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 6 THEN
        Lp = (56 - 16 * LR + LR ^ 2) / 2
    ELSEIF p = 2 AND L = 7 THEN
        Lp = (72 - 18 * LR + LR ^ 2) / 2
    ELSEIF p = 3 AND L = 0 THEN
        Lp = (6 - 18 * LR + 9 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 1 THEN
        Lp = (24 - 36 * LR + 12 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 2 THEN
```

```
        Lp = (60 - 60 * LR + 15 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 3 THEN
        Lp = (120 - 90 * LR + 18 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 4 THEN
        Lp = (210 - 126 * LR + 21 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 5 THEN
        Lp = (336 - 168 * LR + 24 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 6 THEN
        Lp = (504 - 216 * LR + 27 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 3 AND L = 7 THEN
        Lp = (720 - 270 * LR + 30 * LR ^ 2 - LR ^ 3) / 6
    ELSEIF p = 4 AND L = 0 THEN
        Lp = (24 - 96 * LR + 72 * LR ^ 2 - 16 * LR ^ 3 + LR ^ 4) / 24
    ELSEIF p = 4 AND L = 1 THEN
        Lp = (120 - 240 * LR + 120 * LR ^ 2 - 20 * LR ^ 3 + LR ^ 4) /
24
    ELSEIF p = 4 AND L = 2 THEN
        Lp = (360 - 480 * LR + 180 * LR ^ 2 - 24 * LR ^ 3 + LR ^ 4) /
24
    ELSEIF p = 4 AND L = 3 THEN
        Lp = (840 - 840 * LR + 252 * LR ^ 2 - 28 * LR ^ 3 + LR ^ 4) /
24
    ELSEIF p = 4 AND L = 4 THEN
        Lp = (1680 - 1344 * LR + 336 * LR ^ 2 - 32 * LR ^ 3 + LR ^
4) / 24
    ELSEIF p = 4 AND L = 5 THEN
        Lp = (3024 - 2016 * LR + 432 * LR ^ 2 - 36 * LR ^ 3 + LR ^
4) / 24
    ELSEIF p = 4 AND L = 6 THEN
        Lp = (5040 - 2880 * LR + 540 * LR ^ 2 - 40 * LR ^ 3 + LR ^
4) / 24
    ELSEIF p = 4 AND L = 7 THEN
        Lp = (7920 - 3960 * LR + 660 * LR ^ 2 - 44 * LR ^ 3 + LR ^
4) / 24
    ELSEIF p = 5 AND L = 0 THEN
        Lp = (120 - 600 * LR + 600 * LR ^ 2 - 200 * LR ^ 3 + 25 * LR
^ 4 - LR ^ 5) / 120
    ELSEIF p = 5 AND L = 1 THEN
        Lp = (720 - 1800 * LR + 1200 * LR ^ 2 - 300 * LR ^ 3 + 30 *
LR ^ 4 - LR ^ 5) / 120
    ELSEIF p = 5 AND L = 2 THEN
        Lp = (2520 - 4200 * LR + 2100 * LR ^ 2 - 420 * LR ^ 3 + 35
* LR ^ 4 - LR ^ 5) / 120
    ELSEIF p = 5 AND L = 3 THEN
```

```
          Lp = (6720 - 8400 * LR + 3360 * LR ^ 2 - 560 * LR ^ 3 + 40
* LR ^ 4 - LR ^ 5) / 120
     ELSEIF p = 5 AND L = 4 THEN
          Lp = (15120 - 15120 * LR + 5040 * LR ^ 2 - 720 * LR ^ 3 +
45 * LR ^ 4 - LR ^ 5) / 120
     ELSEIF p = 5 AND L = 5 THEN
          Lp = (30240 - 25200 * LR + 7200 * LR ^ 2 - 900 * LR ^ 3 +
50 * LR ^ 4 - LR ^ 5) / 120
     ELSEIF p = 5 AND L = 6 THEN
          Lp = (55440 - 39600 * LR + 9900 * LR ^ 2 - 1100 * LR ^ 3 +
55 * LR ^ 4 - LR ^ 5) / 120
     ELSEIF p = 5 AND L = 7 THEN
          Lp = (95040 - 95040 * LR + 13200 * LR ^ 2 - 1320 * LR ^ 3
+ 60 * LR ^ 4 - LR ^ 5) / 120
     ELSEIF p = 6 AND L = 0 THEN
          Lp = (720 - 4320 * LR + 5400 * LR ^ 2 - 2400 * LR ^ 3 + 450
* LR ^ 4 - 36 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 1 THEN
          Lp = (5040 - 15120 * LR + 12600 * LR ^ 2 - 4200 * LR ^ 3 +
630 * LR ^ 4 - 42 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 2 THEN
          Lp = (20160 - 40320 * LR + 25200 * LR ^ 2 - 6720 * LR ^ 3
+ 840 * LR ^ 4 - 48 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 3 THEN
          Lp = (60480 - 90720 * LR + 45360 * LR ^ 2 - 10080 * LR ^ 3
+ 1080 * LR ^ 4 - 54 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 4 THEN
          Lp = (151200 - 181440 * LR + 75600 * LR ^ 2 - 14400 * LR ^
3 + 1350 * LR ^ 4 - 60 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 5 THEN
          Lp = (332640 - 332640 * LR + 118800 * LR ^ 2 - 19800 * LR
^ 3 + 1650 * LR ^ 4 - 66 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 6 THEN
          Lp = (665280 - 570240 * LR + 178200 * LR ^ 2 - 26400 * LR
^ 3 + 1980 * LR ^ 4 - 72 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 6 AND L = 7 THEN
          Lp = (1235520 - 926640 * LR + 257400 * LR ^ 2 - 34320 *
LR ^ 3 + 2340 * LR ^ 4 - 78 * LR ^ 5 + LR ^ 6) / 720
     ELSEIF p = 7 AND L = 0 THEN
          Lp = (5040 - 35280 * LR + 52920 * LR ^ 2 - 29400 * LR ^ 3
+ 7350 * LR ^ 4 - 882 * LR ^ 5 + 49 * LR ^ 6 - LR ^ 7) / 5040
     ELSEIF p = 7 AND L = 1 THEN
          Lp = (40320 - 141120 * LR + 141120 * LR ^ 2 - 58800 * LR ^
3 + 11760 * LR ^ 4 - 1176 * LR ^ 5 + 56 * LR ^ 6 - LR ^ 7) / 5040
```

```
        ELSEIF p = 7 AND L = 2 THEN
                Lp = (181440 - 423360 * LR + 317520 * LR ^ 2 - 105840 *
LR ^ 3 + 17640 * LR ^ 4 - 1512 * LR ^ 5 + 63 * LR ^ 6 - LR ^ 7) / 5040
        ELSEIF p = 7 AND L = 3 THEN
                Lp = (604800 - 1058400 * LR + 635040 * LR ^ 2 - 176400 *
LR ^ 3 + 25200 * LR ^ 4 - 1890 * LR ^ 5 + 70 * LR ^ 6 - LR ^ 7) / 5040
        ELSEIF p = 7 AND L = 4 THEN
                Lp = (1663200 - 2328480 * LR + 1164240 * LR ^ 2 - 277200
* LR ^ 3 + 34650 * LR ^ 4 - 2310 * LR ^ 5 + 77 * LR ^ 6 - LR ^ 7) / 5040
        ELSEIF p = 7 AND L = 5 THEN
                Lp = (3991680 - 4656960 * LR + 1995840 * LR ^ 2 - 415800
* LR ^ 3 + 46200 * LR ^ 4 - 2772 * LR ^ 5 + 84 * LR ^ 6 - LR ^ 7) / 5040
        ELSEIF p = 7 AND L = 6 THEN
                Lp = (8648640 - 8648640 * LR + 3243240 * LR ^ 2 - 600600
* LR ^ 3 + 60060 * LR ^ 4 - 3276 * LR ^ 5 + 91 * LR ^ 6 - LR ^ 7) / 5040
        ELSEIF p = 7 AND L = 7 THEN
                Lp = (17297280 - 15135120 * LR + 5045040 * LR ^ 2 -
840840 * LR ^ 3 + 76440 * LR ^ 4 - 3822 * LR ^ 5 + 98 * LR ^ 6 - LR ^
7) / 5040
        END IF
SINTENSITY = ((RAMPLITUDE / Wz) ^ 2) * (((2 * (x ^ 2 + Y ^ 2) / (Wz ^
2))) ^ L) * (Lp ^ 2) * ((COS((L * ATN(Y / x)) - (L * (pi / 2)) + angle)) ^ 2) *
EXP((-2 * (x ^ 2 + Y ^ 2)) / (Wz ^ 2))
REM added phase angle (positive) for clockwise rotation.
PIXEL(x) = SINTENSITY
PRINT #2, PIXEL(x);
IF SINTENSITY > MAX THEN
      MAX = SINTENSITY
      END IF
NEXT x
PRINT #2,
NEXT Y
CLOSE #2
REM
NORM:
REM
REM          **** THE STARTING OF NORMALIZATION***
REM
OPEN DATAOUT$ FOR INPUT AS #3
FILEOUT$ = array$ + ".nor"
OPEN FILEOUT$ FOR OUTPUT AS #4
      PRINT
      PRINT "        Normalizing"
      DO UNTIL EOF(3)
```

```
    FOR x = 1 TO 128                          'NORMNUM!
      INPUT #3, VALUE(x)
      IF VALUE(x) = 0 THEN
            NVAL(x) = 0
            PRINT #4, NVAL(x);
      ELSE NVAL(x) = VALUE(x) / MAX
            PRINT #4, NVAL(x);
      END IF
    NEXT x
    PRINT #4,
    LOOP
CLOSE #3
CLOSE #4
REM ******** DATA REDUCTION OF ARRAY ********
REM **** REDUCTION OF A 128X128 TO A 32X32 ARRAY********
PRINT
PRINT "         Reducing Data"
OPEN FILEOUT$ FOR INPUT AS #5
ARRAYOUT$ = array$ + ".ARY"
OPEN ARRAYOUT$ FOR OUTPUT AS #6
    DO UNTIL EOF(5)
    FOR b = 1 TO 32
      FOR x = 1 TO 32
      INPUT #5, VAL10(x), VAL20(x), VAL30(x), VAL40(x)
      FIRTVAL(x) = (VAL10(x) + VAL20(x) + VAL30(x) + VAL40(x)) / 4
      NEXT x
      FOR Y = 1 TO 32
      INPUT #5, VAL11(Y), VAL21(Y), VAL31(Y), VAL41(Y)
      SECTVAL(Y) = (VAL11(Y) + VAL21(Y) + VAL31(Y) + VAL41(Y)) / 4
      NEXT Y
      FOR Z = 1 TO 32
      INPUT #5, VAL12(Z), VAL22(Z), VAL32(Z), VAL42(Z)
      THRTVAL(Z) = (VAL12(Z) + VAL22(Z) + VAL32(Z) + VAL42(Z)) / 4
      NEXT Z
      FOR Q = 1 TO 32
      INPUT #5, VAL14(Q), VAL24(Q), VAL34(Q), VAL44(Q)
      FTHTVAL(Q) = (VAL14(Q) + VAL24(Q) + VAL34(Q) + VAL44(Q)) /
4
      NEXT Q
      FOR J = 1 TO 32              'X LINE LOOP
    TOTALVAL(J) = (FIRTVAL(J) + SECTVAL(J) + THRTVAL(J) +
FTHTVAL(J)) / 4
    PRINT #6, TOTALVAL(J);
    NEXT J
```

```
    PRINT #6,
    NEXT b
    LOOP
      CLOSE #5
      CLOSE #6
      GOTO MAIN
MIX:
REM
REM    Begin mixing files
50 CLS
totamp = 0
MAX = 0
PRINT
      INPUT "   How many files are being mixed? ", number2
      PRINT
      INPUT "   Enter name of new file:   "; array$
      Y = 1
      DATAOUT$ = array$ + ".BIG"
      OPEN DATAOUT$ FOR OUTPUT AS #100
      PRINT
      INPUT "   Enter name of name of existing file to mix:  ", MIX1$
      PRINT
      PRINT "   Total amplitude is at :   "; totamp; " percent."
      PRINT
      INPUT "   Enter the desired mode amplitude (0 to 100 percent): ",
amp(Y)
      PRINT
      totamp = totamp + amp(Y)
      IF totamp > 100 THEN
            PRINT
            PRINT "   Amplitude total can not exceed 100 percent. "
            PRINT "   Please redo mixing.  "
            PRINT
            GOTO 50
      END IF
      MIXED1$ = MIX1$ + ".BIG"

REM
SUMARRAY = 0
      OPEN MIXED1$ FOR INPUT AS #1
      FOR I = 1 TO 128
      FOR J = 1 TO 128
      INPUT #1, MODE(I, J)
      SUMARRAY = SUMARRAY + MODE(I, J)
```

```
      NEXT J
      NEXT I
      CLOSE #1
      MODE1$ = MIX1$ + ".MOD"
      OPEN MODE1$ FOR OUTPUT AS #2
      FOR I = 1 TO 128
      FOR J = 1 TO 128
      IF MODE(I, J) = 0! THEN
            ARRAYNORM = 0
            PRINT #2, ARRAYNORM;
      ELSE
            ARRAYNORM = MODE(I, J) / SUMARRAY
            PRINT #2, ARRAYNORM;
      END IF
      NEXT J
      PRINT #2,
      NEXT I
      CLOSE #2
REM
      OPEN MODE1$ FOR INPUT AS #1
      FOR I = 1 TO 128
      FOR J = 1 TO 128
      INPUT #1, MIXED(I, J)
      SUM(I, J) = MIXED(I, J) * (amp(Y) / 100)
      NEXT J
      NEXT I
      CLOSE #1
FOR Y = 2 TO number2
      INPUT "   Enter name of name of Next existing file to mix:  ", MIX$
      PRINT
      PRINT "   Total amplitude is at :   "; totamp; " percent."
      PRINT
      INPUT "   Enter the desired mode amplitude (0 to 100 percent): ",
amp(Y)
      PRINT
      totamp = totamp + amp(Y)

      IF totamp > 100 THEN
            PRINT
            PRINT "   Amplitude total can not exceed 100 percent. "
            PRINT "   Please redo mixing.  "
            PRINT
            GOTO 50
      ELSEIF Y = number2 AND totamp < 100 THEN
```

```
            PRINT
            PRINT "   Amplitude total must equal 100.   "
            PRINT "   Please redo mixing.   "
            GOTO 50
        END IF
REM NORMALIZATION OF MODES
        MIXED$ = MIX$ + ".BIG"
SUMARRAY = 0
        OPEN MIXED$ FOR INPUT AS #1
        FOR I = 1 TO 128
        FOR J = 1 TO 128
        INPUT #1, MODE(I, J)
        SUMARRAY = SUMARRAY + MODE(I, J)
        NEXT J
        NEXT I
        CLOSE #1
        MODE$ = MIX$ + ".MOD"
        OPEN MODE$ FOR OUTPUT AS #2
        FOR I = 1 TO 128
        FOR J = 1 TO 128
        IF MODE(I, J) = 0! THEN
            ARRAYNORM = 0
            PRINT #2, ARRAYNORM;
        ELSE
            ARRAYNORM = MODE(I, J) / SUMARRAY
            PRINT #2, ARRAYNORM;
        END IF
        NEXT J
        PRINT #2,
        NEXT I
        CLOSE #2
REM
        OPEN MODE$ FOR INPUT AS #(Y)
        FOR I = 1 TO 128
        FOR J = 1 TO 128
        INPUT #(Y), MIXED(I, J)
        SUM(I, J) = SUM(I, J) + (MIXED(I, J) * (amp(Y) / 100))
        NEXT J
        NEXT I
        CLOSE #(Y)
NEXT Y
        FOR I = 1 TO 128
        FOR J = 1 TO 128
        PRINT #100, SUM(I, J);
```

```
        IF SUM(I, J) > MAX THEN
        MAX = SUM(I, J)
        END IF
        NEXT J
        PRINT #100,
        NEXT I
        CLOSE #100

GOTO NORM:

plot:
REM
REM             *** Plotting an existing array file ***
REM                  *** VGA mode 320x200 ***
DEFDBL R-T
CLS
PRINT
PRINT
PRINT "Existing Arrays "
PRINT
SHELL "dir *.nor /B"
PRINT
PRINT
PRINT
INPUT "WHAT IS The Array NAME to Plot? ", array$
PRINT "    "
PRINT "    "
INPUT "Gray Scale (1) or Color (2)?", EYE
PRINT "    "
PRINT "    "
PRINT
IF EYE = 1 THEN
      GOTO GRAY
   ELSEIF EYE = 2 THEN
      GOTO Contrast
   ELSE PRINT "TRY AGAIN (1 OR 2)"
      GOTO plot
   END IF
CLS
Contrast:
SCREEN 13
PALETTE 0, 0          '2097152 (32)  4128768 menu blue(63)  2105376
md. gray
PALETTE 1, 393216
```

```
PALETTE 2, 786432
PALETTE 3, 1179648
PALETTE 4, 1572864
PALETTE 5, 1966080
PALETTE 6, 2359296
PALETTE 7, 2752512
PALETTE 8, 3145728
PALETTE 9, 3538944
PALETTE 10, 3932160
PALETTE 11, 4128768
REM blue-green
PALETTE 12, 4128768
PALETTE 13, 4130304
PALETTE 14, 4131840
PALETTE 15, 4133376
PALETTE 16, 4134912
PALETTE 17, 4136448
PALETTE 18, 4137984
PALETTE 19, 4139520
PALETTE 20, 4141056
PALETTE 21, 4142592
PALETTE 22, 4144128
PALETTE 23, 4144896
REM green
PALETTE 24, 3948288
PALETTE 25, 3555072
PALETTE 26, 3161856
PALETTE 27, 2768640
PALETTE 28, 2375424
PALETTE 29, 1982208
PALETTE 30, 1588992
PALETTE 31, 1195776
PALETTE 32, 802560
PALETTE 33, 409344
PALETTE 34, 16128
REM green-red
PALETTE 35, 16128
PALETTE 36, 16134
PALETTE 37, 16140
PALETTE 38, 16146
PALETTE 39, 16152
PALETTE 40, 16158
PALETTE 41, 16164
PALETTE 42, 16170
```

```
PALETTE 43, 16176
PALETTE 44, 16182
PALETTE 45, 16188
PALETTE 46, 16191
REM red
PALETTE 47, 15423
PALETTE 48, 13887
PALETTE 49, 12351
PALETTE 50, 10815
PALETTE 51, 9279
PALETTE 52, 7743
PALETTE 53, 6207
PALETTE 54, 4671
PALETTE 55, 3135
PALETTE 56, 1599
PALETTE 57, 63
PALETTE 58, 657983
PALETTE 59, 1315903
PALETTE 60, 1973823
PALETTE 61, 2631743
PALETTE 62, 3289663
PALETTE 63, 4144959
PALETTE 65, 0
GOTO Image
GRAY:
REM ****Mapping palette to Gray Scale*****
SCREEN 13
PALETTE 0, 1507328          '2097152 (32)  4128768 menu blue(63)
2105376 md. gray
PALETTE 1, 65793
PALETTE 2, 131586
PALETTE 3, 197379
PALETTE 4, 263172
PALETTE 5, 328965
PALETTE 6, 394758
PALETTE 7, 460551
PALETTE 8, 526344
PALETTE 9, 592137
PALETTE 10, 657930
PALETTE 11, 723723
PALETTE 12, 789516
PALETTE 13, 855309
PALETTE 14, 921102
PALETTE 15, 986895
```

```
PALETTE 16, 1052688
PALETTE 17, 1118481
PALETTE 18, 1184274
PALETTE 19, 1250067
PALETTE 20, 1315860
PALETTE 21, 1381653
PALETTE 22, 1447446
PALETTE 23, 1513239
PALETTE 24, 1579032
PALETTE 25, 1644825
PALETTE 26, 1710618
PALETTE 27, 1776411
PALETTE 28, 1842204
PALETTE 29, 1907997
PALETTE 30, 1973790
PALETTE 31, 2039583
PALETTE 32, 2105376
PALETTE 33, 2171169
PALETTE 34, 2236962
PALETTE 35, 2302755
PALETTE 36, 2368548
PALETTE 37, 2434341
PALETTE 38, 2500134
PALETTE 39, 2565927
PALETTE 40, 2631720
PALETTE 41, 2697513
PALETTE 42, 2763306
PALETTE 43, 2829099
PALETTE 44, 2894892
PALETTE 45, 2960685
PALETTE 46, 3026478
PALETTE 47, 3092271
PALETTE 48, 3158064
PALETTE 49, 3223857
PALETTE 50, 3289650
PALETTE 51, 3355443
PALETTE 52, 3421236
PALETTE 53, 3487029
PALETTE 54, 3552822
PALETTE 55, 3618615
PALETTE 56, 3684408
PALETTE 57, 3750201
PALETTE 58, 3815994
PALETTE 59, 3881787
```

```
PALETTE 60, 3947580
PALETTE 61, 4013373
PALETTE 62, 4079166
PALETTE 63, 4144959
PALETTE 65, 0
Image:
REM ************* Drawing a box ***************
irow = 15                           'Start at upper-left corner
icol = 7
PRESET (icol, irow)
DRAW "c63"                  'WAS C15 WHITE
DRAW "R135 d135 l135 u135"
REM **********************DRAWING IN 32X32 ARRAY
BOXES*************
DRAW "C15"                          'WAS c1 WHICH IS DK BLUE
DRAW "BD3 BL1"
FOR I = 1 TO 32
DRAW "BR4 R4 D4 L4 U4"              'DRAWS 1ST ROW OF BOXES
NEXT I
FOR K = 1 TO 31
DRAW "BD4 BL128"                    'RESETS LOCATION TO START
FOR J = 1 TO 32
DRAW "BR4 R4 D4 L4 U4"              'DRAWS ARRAYS OF BOXES
NEXT J
NEXT K
REM ********FILL-IN GRAYSCALE CHART WITH SHADES******
irow = 175                          'Start at upper-left corner
icol = 25
PRESET (icol, irow)
DRAW "c63"                    ' c15 white
DRAW "R257 D8 L257 U8"
FOR icolor = 0 TO 63
FOR index1 = 1 TO 4
icol = icol + 1
FOR irow = 176 TO 182
   IF icolor = 0 THEN
   icolor = 65
   END IF
   PRESET (icol, irow), icolor
   NEXT irow
   NEXT index1
   IF icolor = 65 THEN
   icolor = 0
   END IF
```

```
NEXT icolor
REM **************BEGIN FILLING 32X32 ARRAY**************
CLOSE #7
BOXOUT$ = array$ + ".ARY"                    '.NOS FOR NOISE PLOTS
OPEN BOXOUT$ FOR INPUT AS #7
FOR irow = 19 TO 143 STEP 4               '19-174 AND STEP5 number of
rows
   FOR icol = 12 TO 136 STEP 4         '12-167NUMBER OF pixels PLUS
STARTING added 450 shift
      PRESET (icol, irow)
      INPUT #7, boxval#
        IF boxval# > 1 THEN
              inbox = 63
        ELSE inbox = boxval# * 63
        END IF
        outbox = CINT(inbox)
        IF outbox = 0! THEN
        outbox = 65
        END IF
        b = 15
        DRAW "p=" + VARPTR$(outbox) + ",=" + VARPTR$(b)
  NEXT icol
NEXT irow
CLOSE #7
REM ***************** BEGIN PLOTTING FILE **************
irow = 15                          'Start at upper-left corner
icol = 166
PRESET (icol, irow)
DRAW "c63"                    'WAS C15 WHITE
DRAW "R135 d135 l135 u135"
CLOSE #8
PLOTOUT$ = array$ + ".nor"
OPEN PLOTOUT$ FOR INPUT AS #8
FOR irow = 19 TO 146                        ' number of rows
   FOR icol = 170 TO 297              'NUMBER OF pixels PLUS STARTING
added 450 shift
     INPUT #8, rvalue#
        inpixel = rvalue# * 63
        outpixel = CINT(inpixel)
        IF outpixel = 0! THEN
        outpixel = 65
        END IF
   PRESET (icol, irow), outpixel
   NEXT icol
```

```
NEXT irow
CLOSE #8
REM LOCATE 11, 68
REM PRINT "1.0"
REM LOCATE 27, 68
REM PRINT "0.0"
REM        LOCATE 27, 12
REM       PRINT TAB(5); "Press space bar to continue"
      DO
      LOOP WHILE INKEY$ = ""
CLS
GOTO MAIN
CORR:
REM This module compares a test file(with noise added) to a reference file(no
noise)
REM and preforms a correlation between the two files.
CLS
PRINT
PRINT "
*****************************************************************
**"
PRINT "       *              Correlation Menu              *"
PRINT "
*****************************************************************"
PRINT "       *                                        *"
PRINT "       *                                        *"
PRINT "       *            1) List Existing Test Arrays        *"
PRINT "       *                                        *"
PRINT "       *            2) Correlation Process           *"
PRINT "       *                                        *"
PRINT "       *            3) Main Menu                *"
PRINT "       *                                        *"
PRINT "       *         Choose one of the following.          *"
PRINT "       *                                        *"
PRINT "
*****************************************************************"
PRINT
INPUT ans1
IF ans1 = 1 GOTO DIR2
IF ans1 = 2 GOTO MODIFY
IF ans1 = 3 GOTO MAIN
DIR2:
CLS
PRINT
```

```
PRINT
PRINT "Existing Arrays "
PRINT
SHELL "dir *.NOR /B"
PRINT
PRINT
    PRINT "Press space bar to continue"
    DO
    LOOP WHILE INKEY$ = ""
GOTO CORR
MODIFY:
CLS
PRINT
INPUT "   Enter the Reference file (no noise)  :  ", file3$
PRINT
INPUT "    Enter file to test against (noise added) :  "; file1$
filenam1$ = file1$ + ".ARY"
filenam2$ = file1$ + ".nos"
filenam3$ = file3$ + ".ary"
FOR noise = 0 TO .50001 STEP .1          'standard devation
IF noise = .2 GOTO 2010
IF noise = .4 GOTO 2010
REM initialize the time for different random numbers.
OPEN filenam1$ FOR INPUT AS #1
OPEN filenam2$ FOR OUTPUT AS #2
REM Gaussian Noise Routine ...see Numerical recipes Pg. 202.
RANDOMIZE TIMER
FOR I = 1 TO 32
FOR J = 1 TO 32
REM RND function creates a random number from 0 to 1.
2000 v1 = RND
v2 = RND
R = v1 ^ 2 + v2 ^ 2
IF R > 1 THEN GOTO 2000
fac = (-2 * LOG(R) / R) ^ .5
gset = v1 * fac * noise
REM gasdev = v2 * fac * noise
IF gset > 1 THEN GOTO 2000
INPUT #1, numb1
PRINT #2, numb1 + gset;
NEXT J
PRINT #2,
NEXT I
CLOSE #2
```

```
CLOSE #1
OPEN filenam3$ FOR INPUT AS #3
OPEN filenam2$ FOR INPUT AS #2
TOPSUM = 0
BOT1SUM = 0
BOT2SUM = 0
TEST1 = 0
REF1 = 0
FOR K = 1 TO 32
FOR L = 1 TO 32
INPUT #2, TEST1
INPUT #3, REF1
TOPSUM = TOPSUM + (TEST1 * REF1)
BOT1SUM = BOT1SUM + (TEST1 ^ 2)
BOT2SUM = BOT2SUM + (REF1 ^ 2)
NEXT L
NEXT K
CORREL = TOPSUM / ((BOT1SUM ^ .5) * (BOT2SUM ^ .5))
PRINT
PRINT "   Noise Factor : "; noise, "  CORRELATION VALUE :  "; CORREL
CLOSE #2
CLOSE #3
2010 NEXT noise
PRINT
     PRINT "Press space bar to continue"
     DO
     LOOP WHILE INKEY$ = ""

GOTO CORR
1000   END
```

VITA

Jimmy Dean Sisco was born in Dayton, Ohio on August 23, 1963. He attended elementary school in Fairborn, Ohio until the fourth grade. The remainder, elementary through high school graduation in 1981 he attended Pasadena City Schools in Pasadena, Texas. The follow year he attended San Jancinto Junior College in Pasadena, Texas and received an Associates Degree in Electronics Technology. In December 1989, he received a Bachelors of Science Degree in Electro-Optics from The University of Houston/Clear-Lake, Natural and Applied Sciences Department, Houston, Texas. In May 1990 he entered The University of Tennessee Space Institute, Tullahoma, TN and in Spring 1996 received a Master of Science Degree in Engineering Science and Mechanics.

He is presently employed as a Space Projects Research Engineer/ Research Laboratory Manager at Space Systems Test Branch, Arnold Engineering Development Center, Arnold Air Force Base, Tullahoma, TN.