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COMPUTER-AIDED OPTICAL LENS DESIGN AND IMAGE ANALYSIS

William D. Hyman, et al

Army Missile Command
Redstone Arsenal, Alabama

20 August 1973

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13. ABSTRACT

At the core of the US Army Missile Command's (MICOM's) capability to design and analyze optical system performance is a computer program written for the National Aeronautics and Space Administration (NASA) called Fortran Optical Lens Design Program (FOLDP). Personnel at MICOM have modified this program to utilize the available SC 4020 digital computer plotter and developed a program to do a complete analysis of the image produced by the finished design. The modifications required on the basic program are discussed and a complete description of the Image Analysis Program and user guidelines are presented. The Image Analysis Program can be used in conjunction with any raytrace program which yields ray coordinates and direction cosines on the final optical surface as its end product.

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Design/raytrace operation						
Image analysis operation						
Spot diagram						
Modulation frequency limits						
Aperture scan step size						

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INTRODUCTION

The US Army Missile Command (MICOM) has developed an inhouse capability to design, optimize, and analyze the image from complex optical systems. A lens design program which was written for the National Aeronautics and Space Administration (NASA) was used as the basic design program and modifications were performed on it to make it compatible with the SC 4020 digital computer plotter routines.

The end product of this program is a compilation of ray coordinates and direction cosines on the final optical surface. These parameters are punched out on data cards and used as an input to a program which was developed inhouse to do a complete analysis of the image. The analysis includes:

1) Plots of the spot diagram and ray path projections on two planes perpendicular to the image plane.

2) Plots of the modulation transfer function of the system derived from the spot diagram.

3) Plots of the image energy distribution derived by scanning an aperture across the spot diagram.

Several advantages are realized by performing the design/raytrace operation separately from the image analysis operation instead of incorporating the Image Analysis Program into FOLDP as a subroutine to be run concurrently:

1) The rays from several runs can be put together to form a composite spot diagram. This is especially helpful in the case of multiple colors or segmented optical elements. If a system is raytraced for a segmented lens over a wide spectral region, then the composite spot diagram must be defined by one run for each combination of color and lens segment. The outputs for all of the cases can be combined by the Image Analysis Program to form a spot diagram representing the total system performance.

2) The control parameters required by the Image Analysis Program can be chosen to yield the most meaningful analysis of the final spot diagram. Parameters such as modulation frequency limits and aperture scan step size can best be determined by knowledge of the spot diagram. This is available as the end product of FOLDP and can be used to choose the input parameters for the Image Analysis Program.

3) The image plane may be moved to various positions relative to the final optical element without the necessity of a rerun of the design/raytrace operation.

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First, the modifications made to the Fortran Optical Lens Design Program (FOLDP) are described, and then the Image Analysis Program is described. An example case run is included to demonstrate the capability of the lens design program and to show the additional information that is gained by processing the spot diagram through the Image Analysis Program.

A complete Fortran listing of the Image Analysis Program is included as Appendix A. A brief outline of the required input cards for the Image Analysis Program is included as Appendix B to give the user who is familiar with the program a quick reference when preparing a case run.

FORTRAN OPTICAL LENS DESIGN PROGRAM (FOLDP)

The FOLDP[1] routines were written for an IBM 7094 machine and have been adapted to run on MICOM's CDC 6600. It was necessary to modify the lens profile plot routines to make them compatible with the SC 4020 plotter which is available to be used in conjunction with the CDC 6600. These routines produce a scaled drawing of the optical system on the SC 4020. An addition to the program was required to extract the raytrace data in the correct sequence of the execution to provide inputs for the image analysis software. The modifications and plot routines will not be shown here because the program is extensive (7000 cards) and the modifications would not be applicable to another computer or to the same computer with a different plotter. However, the output deck for this program is listed and discussed since almost any general raytrace program can be modified to yield an identical output, and this deck serves as the input to the Image Analysis Program which can be adapted in part or in its entirety to other machines and plotters with a minimum effort.

A. Output Deck

The output deck consists of the following:

1) A card containing an integer quantity (N) equal to the number of rays on the final output surface. Format (I10).

2) A series of N cards each containing the X,Y,Z coordinates of the rays on the final surface and the direction cosines QX,QY,QZ of the rays. Format (6E13.7).

Some other data cards must be added to this deck before it comprises the complete input for the image analysis routines.

The coordinate reference system convention employed for these programs is shown in Figure 1. The Z-axis is the optical axis.

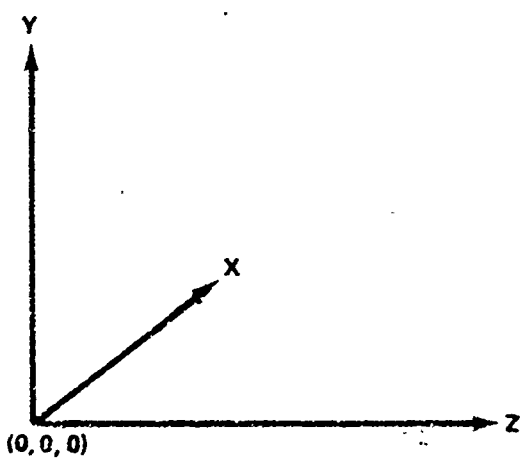

Figure 1. Coordinate reference system.

[1]FOLDP – Fortran Optical Lens Design Program, available from COSMIC, Barrow Hall, University of Georgia, Athens, Georgia 30601 (404-542-3205) 1 October 1968.

A ray is depicted in Figure 2 as it appears in the Y,Z plane for an arbitrary final optical surface.

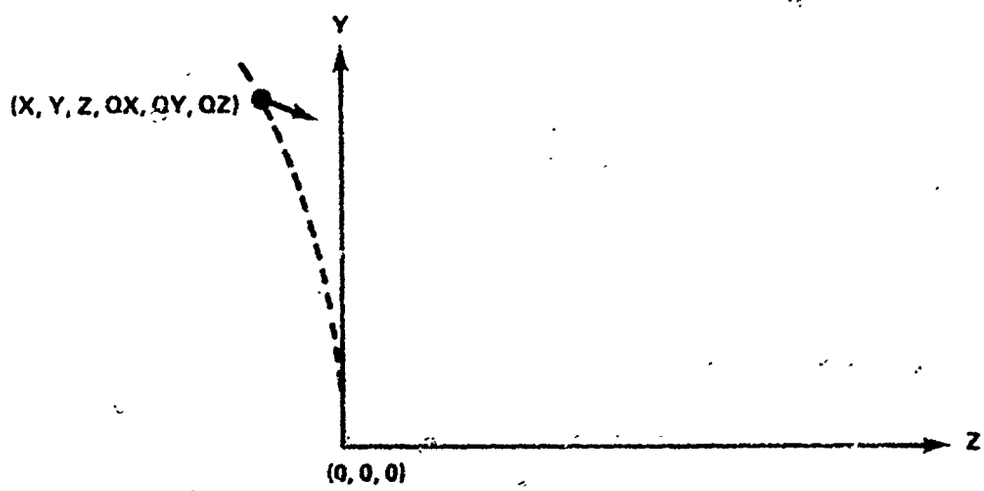

Figure 2. Ray on final surface.

B. Capability

The FOLDP measures the performance of an arbitrary optical system by a merit function which is essentially the sum of the squares of a set of weighted aberrations. Designing is a least squares process for iteratively reducing the magnitude of the merit function by linearly adjusting system parameters. FOLDP can handle systems containing up to 100 surfaces (including aspherics), 7 object points, 6 colors, and 200 rays.

C. Example Case

A Cooke triplet lens system was selected for the example case. Figure 3 shows the system before the optimization is performed. Figure 4 shows the SC 4020 representation of the system after the design iterations have been completed.

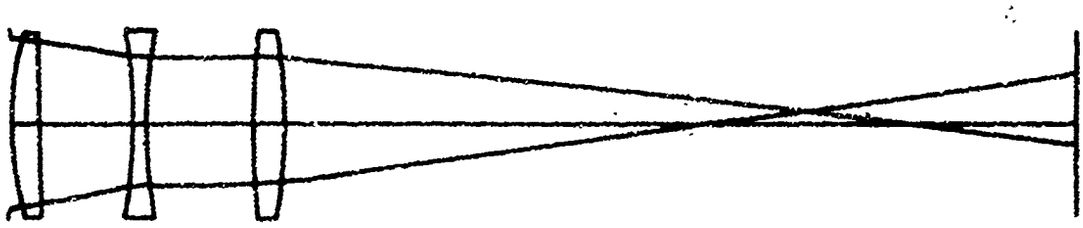

Figure 3. Cooke triplet before design (off-axis object).

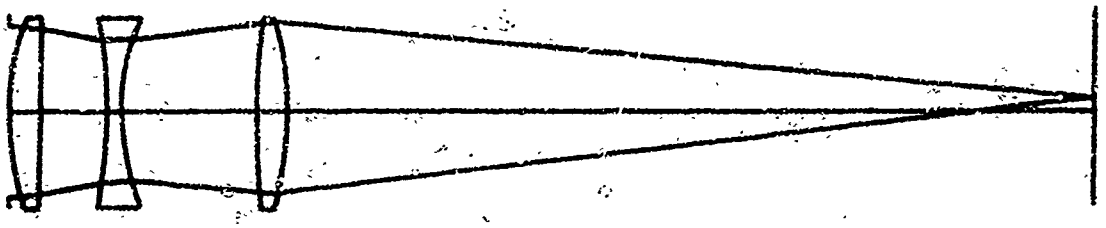

Figure 4. Cooke triplet after design (off-axis object).

The output deck which is punched by FOLDP is listed in Table 1, and the spot diagrams which represent the intersection of these rays with the image plane are reproduced in Figures 5 and 6. These diagrams are produced on the line printer by FOLDP. Figure 7 is simply a representation of the ray pattern on the entrance pupil. The design was performed for two object positions simultaneously: one was on-axis; the other was 1° off-axis. This insures good resolution over the intended field of view of the lens system. The raytrace data were punched by FOLDP for both object positions, so the Image Analysis Program will analyze two separate cases.

TABLE 1. FOLDP OUTPUT DECK

76

.1521808E+00	-.1369627E+01	-.1876969E+00	-.9979185E-02	.8981266E-01	.9959087E+00
-.1521808E+00	-.1369627E+01	-.1876969E+00	.9979185E-02	.8981266E-01	.9959087E+00
.1513267E+00	-.1059287E+01	-.1123314E+00	-.9993353E-02	.6995347E-01	.9975002E+00
-.1513267E+00	-.1059287E+01	-.1123314E+00	.9993353E-02	.6995347E-01	.9975002E+00
.1507208E+00	-.7536039E+00	-.5763626E-01	-.9993003E-02	.4996501E-01	.9987010E+00
-.1507208E+00	-.7536039E+00	-.5763626E-01	.9993003E-02	.4996501E-01	.9987010E+00
.1503318E+00	-.4509955E+00	-.2197705E-01	-.9988501E-02	.2996550E-01	.9995010E+00
-.1503318E+00	-.4509955E+00	-.2197705E-01	.9988501E-02	.2996550E-01	.9995010E+00
.1501416E+00	-.1501416E+00	-.4376801E-02	-.9985129E-02	.9985129E-02	.9999003E+00
-.1501416E+00	-.1501416E+00	-.4376801E-02	.9985129E-02	.9985129E-02	.9999003E+00
.1501416E+00	.1501416E+00	-.4376801E-02	-.9985129E-02	-.9985129E-02	.9999003E+00
-.1501416E+00	.1501416E+00	-.4376801E-02	.9985129E-02	-.9985129E-02	.9999003E+00
.1503318E+00	.4509955E+00	-.2197705E-01	-.9988501E-02	-.2996550E-01	.9995010E+00
-.1503318E+00	.4509955E+00	-.2197705E-01	.9988501E-02	-.2996550E-01	.9995010E+00
.1507208E+00	.7536039E+00	-.5763626E-01	-.9993003E-02	-.4996501E-01	.9987010E+00
-.1507208E+00	.7536039E+00	-.5763626E-01	.9993003E-02	-.4996501E-01	.9987010E+00
.1513267E+00	.1059287E+01	-.1123314E+00	-.9993353E-02	-.6995347E-01	.9975002E+00
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.1521808E+00	.1369627E+01	-.1876969E+00	-.9979185E-02	-.8981266E-01	.9959087E+00
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.4535943E+00	-.9071886E+00	-.1008127E+00	-.2998193E-01	.5996386E-01	.9977502E+00
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-.4509237E+000.		-.1976880E-01	.2996436E-010.		.9995510E+00
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.4535943E+00	.9071886E+00	-.1008127E+00	-.2998193E-01	-.5996386E-01	.9977502E+00
-.4535943E+00	.9071886E+00	-.1008127E+00	.2998193E-01	-.5996386E-01	.9977502E+00
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-.4558046E+00	.1215479E+01	-.1662033E+00	.2995528E-01	-.7988075E-01	.9963542E+00
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.7566333E+00	-.7566333E+00	-.1123314E+00	-.4996677E-01	.4996677E-01	.9975002E+00
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.4509494E+00	.9943478E-01	-.2073429E-01	-.2996305E-01	.1080872E-01	.9994926E+00
-.4509494E+00	.9943478E-01	-.2073429E-01	.2996305E-01	.1080872E-01	.9994926E+00
.4512929E+00	.4001250E+00	-.3542068E-01	-.2996372E-01	-.9164072E-02	.9995090E+00
-.4512929E+00	.4001250E+00	-.3542068E-01	.2996372E-01	-.9164072E-02	.9995090E+00
.4522295E+00	.7018288E+00	-.6809249E-01	-.2996766E-01	-.2914142E-01	.9991260E+00
-.4522295E+00	.7018288E+00	-.6809249E-01	.2996766E-01	-.2914142E-01	.9991260E+00
.4538045E+00	.1005818E+01	-.1195405E+00	-.2996089E-01	-.4909966E-01	.9983444E+00
-.4538045E+00	.1005818E+01	-.1195405E+00	.2996089E-01	.4909966E-01	.9983444E+00
.4561005E+00	.1313560E+01	-.1911707E+00	-.2991577E-01	-.6893921E-01	.9971722E+00
-.4561005E+00	.1313560E+01	-.1911707E+00	.2991577E-01	-.6893921E-01	.9971722E+00
.7594861E+00	-.9656053E+00	-.1485931E+00	-.4997112E-01	.8076728E-01	.9954795E+00
-.7594861E+00	-.9656053E+00	-.1485931E+00	.4997112E-01	.8076728E-01	.9954795E+00
.7564306E+00	-.6580774E+00	-.9848870E-01	-.4999118E-01	.6079517E-01	.9968976E+00
-.7564306E+00	-.6580774E+00	-.9848870E-01	.4999118E-01	.6079517E-01	.9968976E+00
.7544993E+00	-.3539207E+00	-.6784212E-01	-.4998058E-01	.4079317E-01	.9979168E+00
-.7544993E+00	-.3539207E+00	-.6784212E-01	.4998058E-01	.4079317E-01	.9979160E+00
.7536009E+00	-.5175816E-01	-.5566978E-01	-.4996644E-01	.2080070E-01	.9985343E+00
-.7536009E+00	-.5175816E-01	-.5566978E-01	.4996644E-01	.2080070E-01	.9985343E+00

TABLE 1. CONCLUDED

.7536957E+00	.2496468E+00	-.6153815E-01	-.4995874E-01	.8189224E-03	.9987509E+00
-.7536957E+00	.2496468E+00	-.6153815E-01	.4995874E-01	.8189224E-03	.9987509E+00
.7547896E+00	.5514903E+00	-.8550572E-01	-.4995416E-01	-.1915763E-01	.9985678E+00
-.7547896E+00	.5514903E+00	-.8550572E-01	.4995416E-01	-.1915763E-01	.9985678E+00
.7569363E+00	.8550217E+00	-.1281317E+00	-.4993523E-01	-.3911353E-01	.9979863E+00
-.7569363E+00	.8550217E+00	-.1281317E+00	.4993523E-01	-.3911353E-01	.9979863E+00
.7602477E+00	.1161654E+01	-.1905556E+00	-.4986416E-01	-.5897505E-01	.9970133E+00
-.7602477E+00	.1161654E+01	-.1905556E+00	.4986416E-01	-.5897505E-01	.9970133E+00
.1065453E+01	-.8159362E+00	-.1778278E+00	-.6990430E-01	.7073276E-01	.9950428E+00
-.1065453E+01	-.8159362E+00	-.1778278E+00	.6990430E-01	.7073276E-01	.9950428E+00
.1061815E+01	-.5088808E+00	-.1363379E+00	-.6995649E-01	.5078517E-01	.9962565E+00
-.1061815E+01	-.5088808E+00	-.1363379E+00	.6995649E-01	.5078517E-01	.9962565E+00
.1059754E+01	-.2046054E+00	-.1143113E+00	-.6996175E-01	.3079913E-01	.9970741E+00
-.1059754E+01	-.2046054E+00	-.1143113E+00	.6996175E-01	.3079913E-01	.9970741E+00
.1059171E+01	.9824847E-01	-.1109932E+00	-.6995073E-01	.1081261E-01	.9974918E+00
-.1059171E+01	.9824847E-01	-.1109932E+00	.6995073E-01	.1081261E-01	.9974918E+00
.1060040E+01	.4009432E+00	-.1261842E+00	-.6992908E-01	-.9162516E-02	.9975099E+00
-.1060040E+01	.4009432E+00	-.1261842E+00	.6992908E-01	-.9162516E-02	.9975099E+00
.1062407E+01	.7047489E+00	-.1602140E+00	-.6987994E-01	-.2910640E-01	.9971307E+00
-.1062407E+01	.7047489E+00	-.1602140E+00	.6987994E-01	-.2910640E-01	.9971307E+00
.1066400E+01	.1011053E+01	-.2139903E+00	-.6975823E-01	-.4895381E-01	.9963620E+00
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.1371416E+01	-.3600639E+00	-.1989272E+00	-.8979546E-01	.4075552E-01	.9951260E+00
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.1369617E+01	-.5490982E-01	-.1856659E+00	-.8982175E-01	.2080345E-01	.9957406E+00
-.1369617E+01	-.5490982E-01	-.1856659E+00	.8982175E-01	.2080345E-01	.9957406E+00
.1369818E+01	.2494197E+00	-.1916838E+00	-.8979152E-01	.8503990E-03	.9959602E+00
-.1369818E+01	.2494197E+00	-.1916838E+00	.8979152E-01	.8503990E-03	.9959602E+00
.1372035E+01	.5542642E+00	-.2170540E+00	-.8969610E-01	-.1906269E-01	.9957867E+00
-.1372035E+01	.5542642E+00	-.2170540E+00	.8969610E-01	-.1906269E-01	.9957867E+00

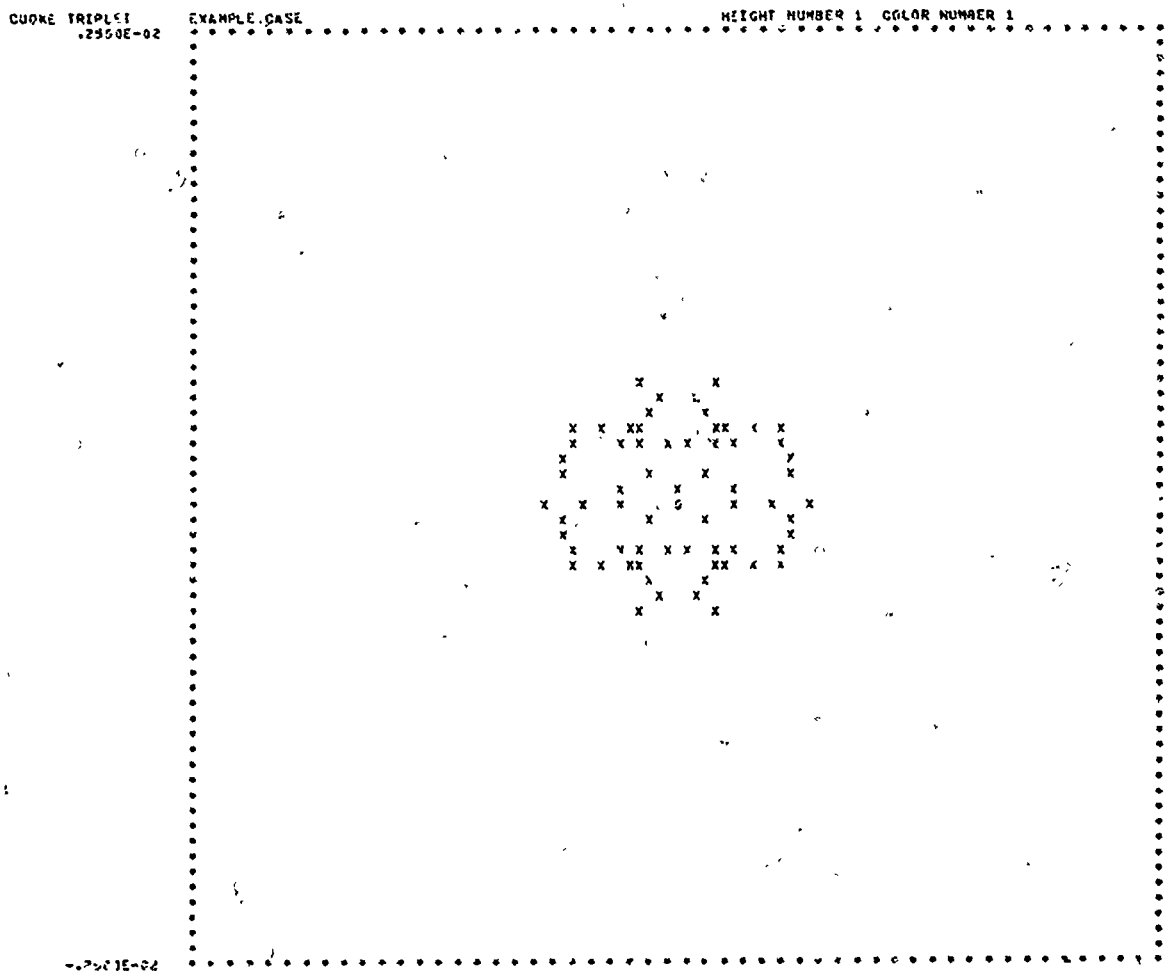


Figure 5. Spot diagram for on-axis object.

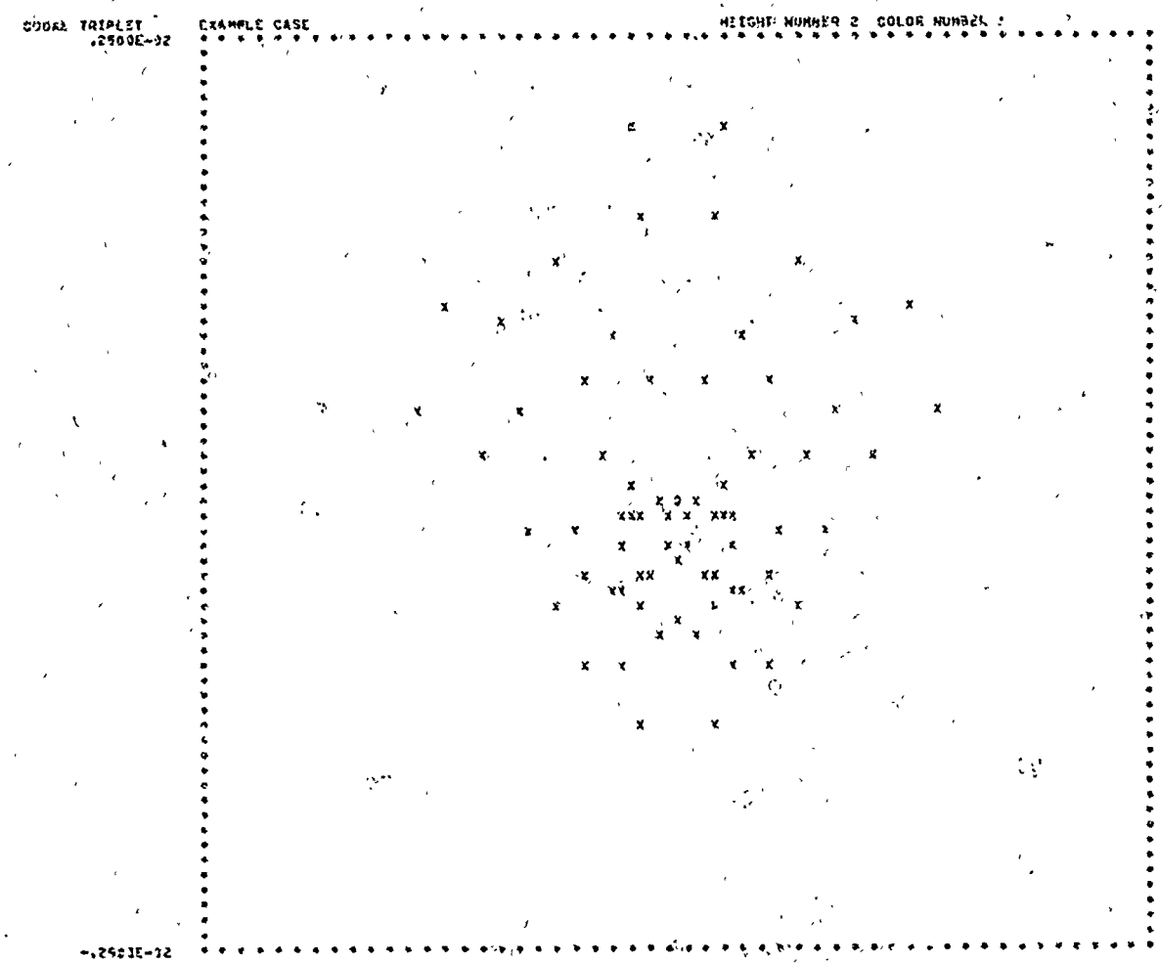


Figure 6. Spot diagram for 1° off-axis object.

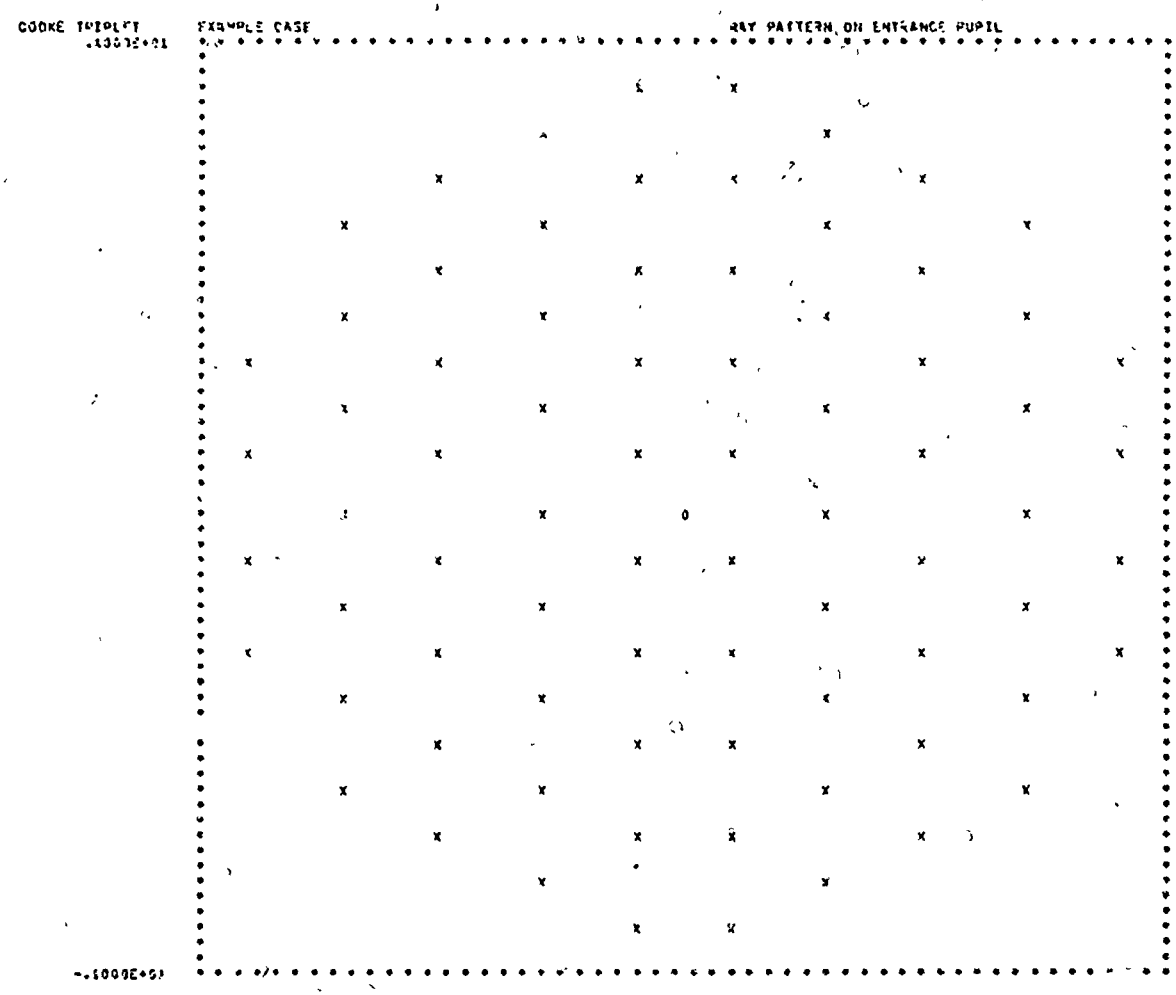


Figure 7. Ray pattern on the entrance pupil.

IMAGE ANALYSIS PROGRAM

The Image Analysis Program was developed to perform a complete image analysis for any optical system which can be raytraced by FOLDP. Since the rays are defined on the final optical surface, the user is free to specify the location of the image plane relative to this surface and examine the image at that plane. The image plane location may be moved and the results examined for the new location without a new raytrace being performed.

A. Main Program

The main program uses the deck punched by the FOLDP routines plus two additional cards listing the run title and the image plane location relative to the final optical surface. The deck consists of the following:

1) A card listing the run title in a field 60 characters wide.

2) A card listing the axial distance of the image plane from the vertex of the final optical surface (DELD). Format (F10.0).

3) A card listing the total number of rays on the final optical surface (N). Format (I10). (Punched by FOLDP).

4) N cards listing the X,Y,Z coordinates of each ray and the associated direction cosines QX,QY,QZ one ray per card. Format (6E13.7). (Punched by FOLDP).

The main program uses these inputs to compute the ray intersect coordinates on the image plane. It then calculates the average X and average Y ray coordinates (centroid) and transforms all rays relative to that point. These values are then stored in COMMON along with the centroid coordinates, the direction cosines, the image plane location, and the run title for use by the program subroutines.

B. Subroutine RAPLOT

1. Purpose

The purpose of subroutine RAPLOT is to plot the ray intersection pattern on the image plane, and also to plot the convergence of the ray bundle as viewed along the two coordinate axes perpendicular to the image plane. These plots, when studied together, give the designer a good "feel" for how the image is formed and whether the image plane is located at the best focus position.

2. Methodology

The RAPLOT subroutine uses the X,Y,Z ray coordinates on the image plane and the associated direction cosines to construct three diagrams:

1) The spot diagram which represents the intersection of the rays with the image plane (X,Y plane) (Figure 8).

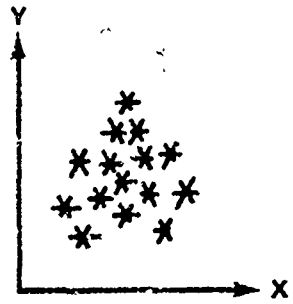


Figure 8. Spot diagram.

2) Projection of the ray paths on the Y,Z plane as reviewed along the X-axis (Figure 9). The intersection point is determined from the Y coordinate and the slope is determined from the direction cosines QY and QZ.

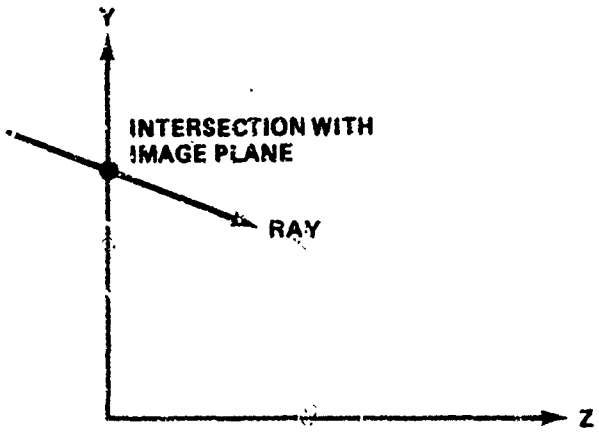


Figure 9. Ray projection on Y,Z plane.

3) Projection of the ray paths on the X,Z plane as viewed along the Y-axis (Figure 10). The intersection point is determined from the X coordinate and the slope is determined from the direction cosines QX and QZ.

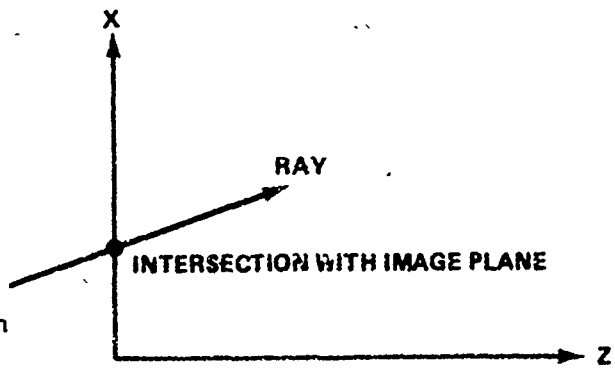


Figure 10. Ray projection on X,Z plane.

3. Input and Output Description

a. Input

The X,Y,Z ray coordinates relative to the pattern centroid and the direction cosines of each ray are available to this subroutine

through the COMMON storage block. The input required for this subroutine is a card containing the values for SCALE, DELTXY, NEMPHS, and NCHRS. The format is (2F10.0, 2I10). SCALE specifies the plot scale such that the rays are plotted on a field centered about the point (0,0) and defined by Figure 11. DELTXY specifies the plot tic increment. NEMPHS specifies the tics which are to be labeled and emphasized. Every NEMPHSth tic is emphasized and labeled. NCHRS specifies the number of characters including the decimal to be written for each label.

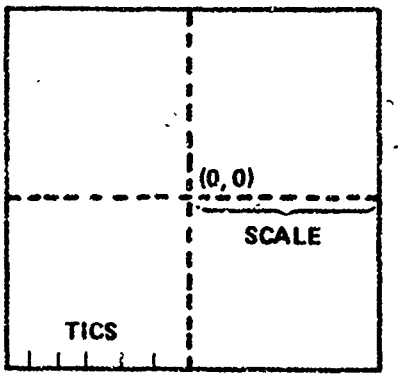


Figure 11. Definition of SCALE.

b. Output

This subroutine provides a hard copy of the image plane location, the ray pattern centroid, and the coordinates of each ray on the image plane. In addition the three plots previously described are drawn by the SC 4020 plotter.

C. Subroutine MTF

1. Purpose

The purpose of subroutine MTF is to compute the modulation transfer function (MTF) of the optical system under consideration and to plot this function.

2. Theory

The modulation transfer function provides a measure of the performance of an optical system. Suppose that the object is a set of light and dark bands, the distribution of brightness being $1 + \cos 2\pi\upsilon' X$. The optical system degrades the image so that the contrast between the bright and dark bands is less. Suppose the image distribution of brightness is $F(X) = a_0 + a_1 \cos 2\pi\upsilon X$. The $MTF(\upsilon)$ is defined to be the ratio between the contrast of the image to the contrast of the object for an image with the spatial frequency υ. In this case, the contrast of the image is a_1/a_0, the contrast of the object is 1, and the $MTF(\upsilon) = a_1/a_0$.

Smith[2] has shown that the MTF can also be derived from the spread function of a point object. Suppose that the image distribution of brightness is $F(X,Y)$. Define the line spread function by $A(X) = \int F(X,Y)$.

[2]Smith, Warren J., Modern Optical Engineering, McGraw Hill, New York. 1966, pp. 300-325.

Then the MTF is given by the expression:

$$MTF(\nu) = \left[A_c^2(\nu) + A_s^2(\nu)\right]^{\frac{1}{2}} \tag{1}$$

where

$$A_c(\nu) = \frac{\int A(X) \cos (2\pi\nu X) dX}{\int A(X) dX} \tag{2}$$

$$A_s(\nu) = \frac{\int A(X) \sin (2\pi\nu X) dX}{\int A(X) dX} \tag{3}$$

and if the line spread function A(X) is asymmetrical, a phase shift ϕ in the pattern image is introduced, described by:

$$\cos \phi = \frac{A_c(\nu)}{|A(\nu)|} \quad \text{or} \quad \tan \phi = \frac{A_s(\nu)}{A_c(\nu)} . \tag{4}$$

3. Methodology

Assume that a spot diagram has been prepared from raytrace data, such that the coordinates X_i, Y_i of each ray intersection on the image plane are known. The line spread function A(X) is represented by the number of rays per interval N(X) (Figures 12 and 13).

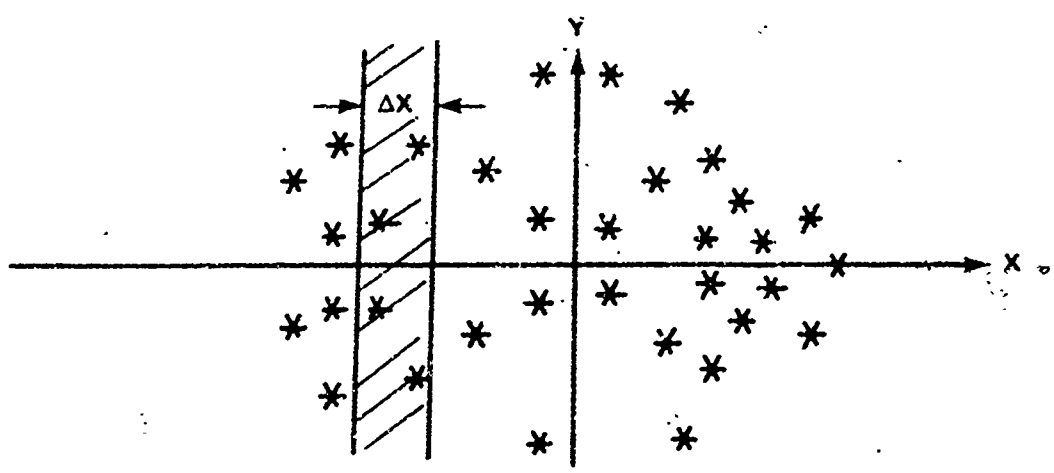


Figure 12. Spot diagram divided into increments of ΔX to count number of rays N_X per ΔX interval.

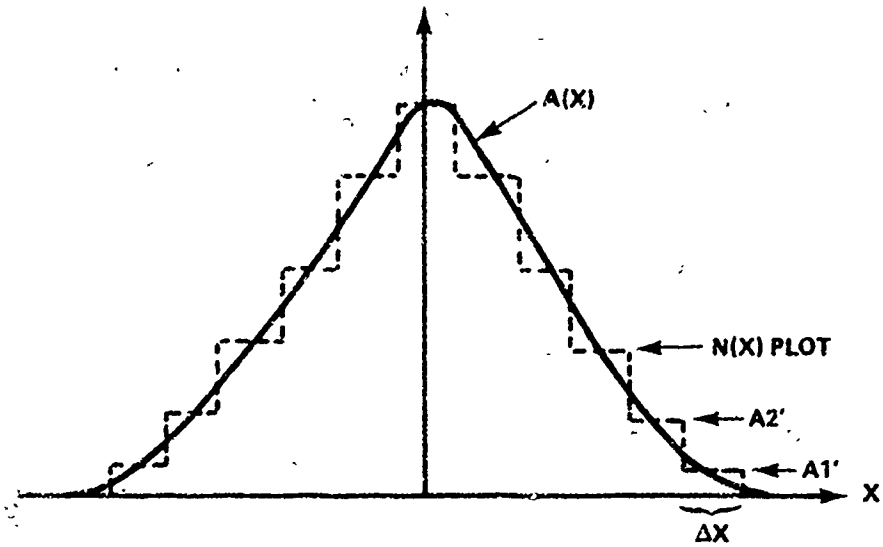


Figure 13. Determining line spread function A(X).

Since A(X) is, in practice, never represented by a continuous function, we must approximate the integrals in Eqs. (2) and (3) by the equivalent sums over the ΔX intervals.

$$A_c(\nu) = \frac{\Sigma N(X) \cos (2\pi\nu X)\Delta X}{\Sigma N(X)\Delta X} \tag{5}$$

$$A_s(\nu) = \frac{\Sigma N(X) \sin (2\pi\nu X)\Delta X}{\Sigma N(X)\Delta X} . \tag{6}$$

We may factor out ΔX to simplify Eqs. (5) and (6):

$$A_c(\nu) = \frac{\Sigma N(X) \cos (2\pi\nu X)}{\Sigma N(X)}$$

$$A_s(\nu) = \frac{\Sigma N(X) \sin (2\pi\nu X)}{\Sigma N(X)} . \tag{7}$$

But $\Sigma N(X)$ equals the total number of rays on the spot diagram, N_{TOTAL}. In the numerators of Eq. (7), the sums over intervals are equivalent to sums over rays. Thus, Eq. (7) becomes

$$A_c(\nu) = \frac{\sum_{i=1}^{N_{TOTAL}} \cos (2\pi\nu X_i)}{N_{TOTAL}} \tag{8}$$

$$A_s(\nu) = \frac{\sum_{i=1}^{N_{TOTAL}} \sin(2\pi\nu X_i)}{N_{TOTAL}} \tag{9}$$

which are the equations that are programmed. Once these are computed the MTF is found from Eq. (1), and the associated phase angle is computed from the second of Eq. (4). This subroutine also includes a feature which permits one to scan the spot pattern from two preselected angles, θ_1 and θ_2. To achieve this, the rotation of axes is performed from the initial coordinate axes as depicted in Figure 14. The coordinate X_i is transformed according to the equation

$$X_i' = X_i \cos\theta + Y_i \sin\theta \tag{10}$$

and the computation of the MTF proceeds as previously discussed, utilizing X_i' in Eqs. (8) and (9).

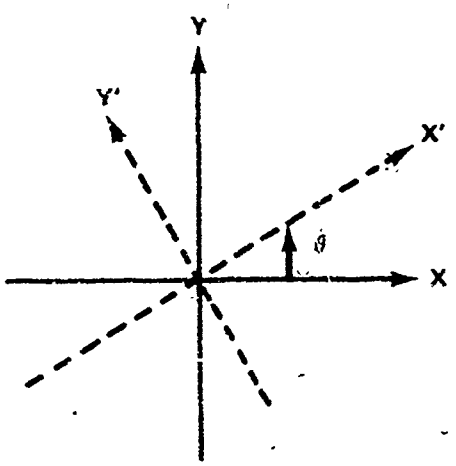


Figure 14. Rotation of axes.

4. Input and Output Description

a. Input

The coordinates (X_i, Y_i) and N_{TOTAL} have previously been computed in the program and are stored in COMMON. The only input required by the user is a card utilizing a (3I10, 4F10.4) format on which the following are punched:

1) An integer which specifies the plot tics which are to be emphasized and labeled. (NEMPHS: I10 format).

2) The number of characters including the decimal to be written for each tic label. (NCHRS: I10 format).

3) The number of frequencies desired (NFREQ: I10 format).

4) The desired starting frequency (STFREQ: F10.4 format).

5) The desired frequency increment (DFREQ: F10.4 format).

6) The first scan angle (THETA(1): F10.4 format).

7) The second scan angle (THETA(2): F10.4 format).

b. Output

This subroutine provides a hard copy output of NFREQ, STFREQ, DFREQ, θ, NEMPHS, and NCHRS values at the top of the page; followed by a columnar listing of the frequency value, the MTF associated with that frequency, and the phase angle. There are NFREQ entries per column, with frequency values running from STFREQ to STFREQ + (NFREQ - 1) x DFREQ. Also provided is a plot of MTF versus frequency via the SC 4020 plotter.

D. Subroutine SCANS

1. Purpose

The purpose of subroutine SCANS is to scan the spot diagram at the image plane of the optical system under consideration, using either a circular or rectangular scanning aperture. The limits of the scanning cycle are set by the user. Knowing the number of rays contained within the aperture at each step of a scan, one can form an idea of the intensity distribution of the image.

2. Theory

It is frequently desirable to determine the density distribution of ray intercepts on the image plane of an optical system. This distribution is, of course, dependent on several factors: the shape and size of the aperture used, the step size used for the scan, the limits chosen for the scanning process, and the intrinsic distribution of rays on the image plane.

3. Methodology

Assume that a spot diagram of N rays has been prepared from raytrace data, such that the coordinates X_i, Y_i of each ray intersection on the image plane are known. All points in the diagram have been transformed to make the centroid the new origin of coordinates in the main program. Thus, in the following, X_i, Y_i will refer to the Ith point referenced to the centroid. However, the user has the option of specifying any origin coordinates (XTR,YTR) he desires. Moreover, if he wishes to rotate the scan axes through a preselected angle θ (counterclockwise), he has this option as well. For example, if the centroid

is used for the scan center and the axes are rotated through an angle of $\theta = 30^{\circ}$, the equations would be:

$$XTR = 0$$

$$YTR = 0$$

$$T1 = X_i - XTR = X_i, \; i = 1, N$$

$$T2 = Y_i - YTR = Y_i, \; i = 1, N$$

$$X_i' = T1 \cos 30^{\circ} + T2 \sin 30^{\circ}, \; i = 1, N$$

$$Y_i' = T1 \sin 30^{\circ} + T2 \cos 30^{\circ}, \; i = 1, N.$$

Note that the translation of axes is done first, followed by the rotation of axes about the new center. We also see that when $\theta = 0$ that $X_i' = X_i$ and $Y_i' = Y_i$, as it must.

Suppose that we have completed the desired translation/rotation process and now have our spot diagram in a form ready for scanning. We must now use some aperture to scan this diagram. The shape and the dimensions of the aperture follow this convention (Figure 15).

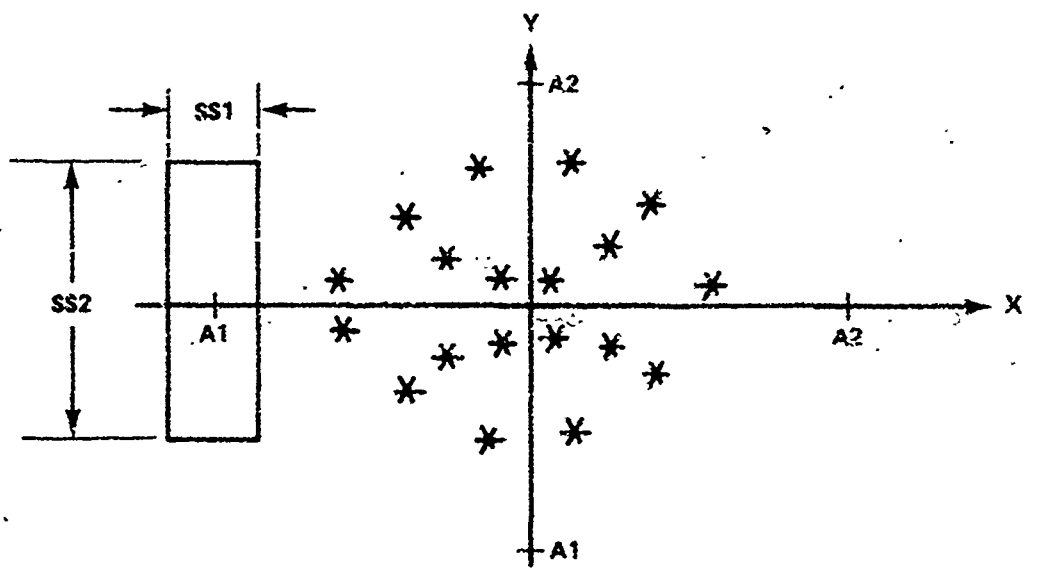


Figure 15. Rectangular aperture used for scanning along X-axis.

If the aperture is rectangular, SS1 is the horizontal (X) dimension of aperture and SS2 is the vertical (Y) dimension of aperture. For a circular aperture, SS1 and SS2 = 2R where R is the radius of the circle. The number of steps NS in the scan is determined by the programmer and

entered as data. The scan step size is defined by the equation SS = (A2 - A1)/(NS - 1). We now proceed to scan as illustrated in Figure 16.

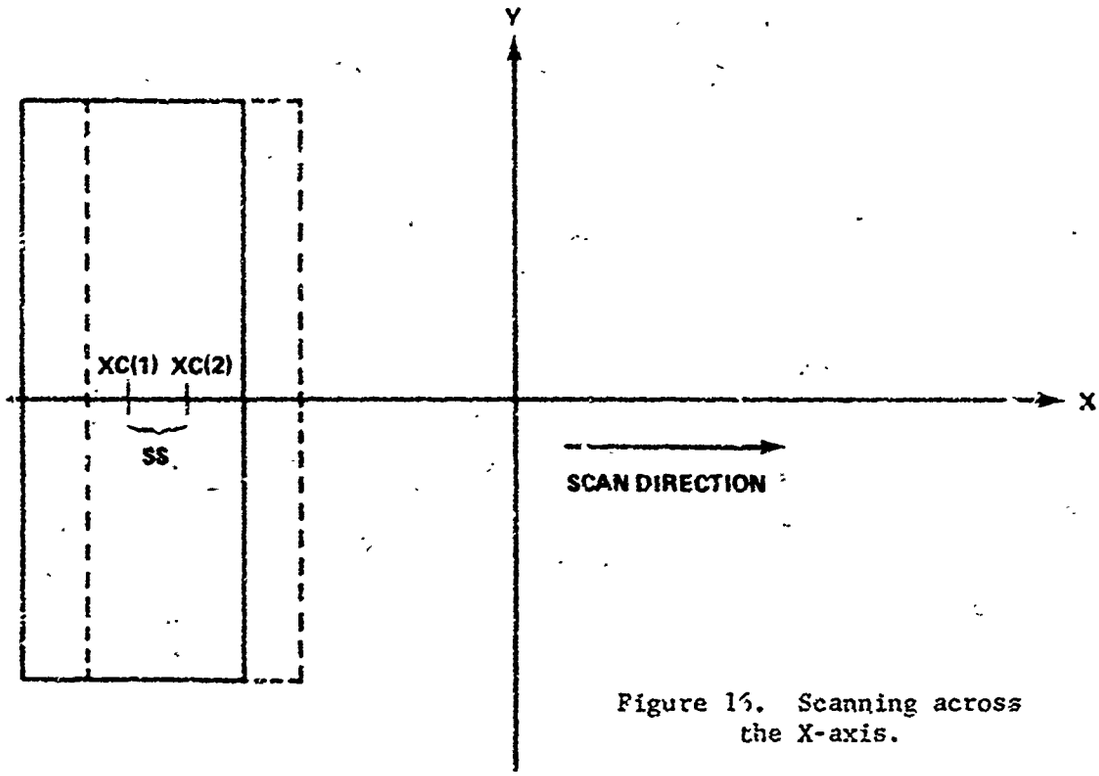


Figure 16. Scanning across the X-axis.

XC(J) is the position of the center of the scanning aperture during each scan step. Initially, XC(1) = A1. The scan is performed from A1 to A2 in steps of SS for a total of NS positions. For a given aperture position, we count the number of rays lying on or within the scanning aperture boundaries by utilizing a counter, NPMC, which will increment by 1 each time the following conditions are met by the X_i, Y_i points:

$$\left.\begin{array}{r} |X_i' - XC(J)| \le SS1/2 \\ |Y_i| \le SS2/2 \end{array}\right\} \text{ rectangular aperture}$$

$$\left[X_i' - XC(J)\right]^2 + \left[Y_i'\right]^2 \le R^2 \quad \text{circular aperture}$$

What is now required is to find the counter with the largest number of rays and normalize the other counters to it. This process yields the relative intensity as a function of aperture position.

When the X-axis scan is completed, a scan of the Y-axis is then begun, from Y = A1 to Y = A2 (Figure 17).

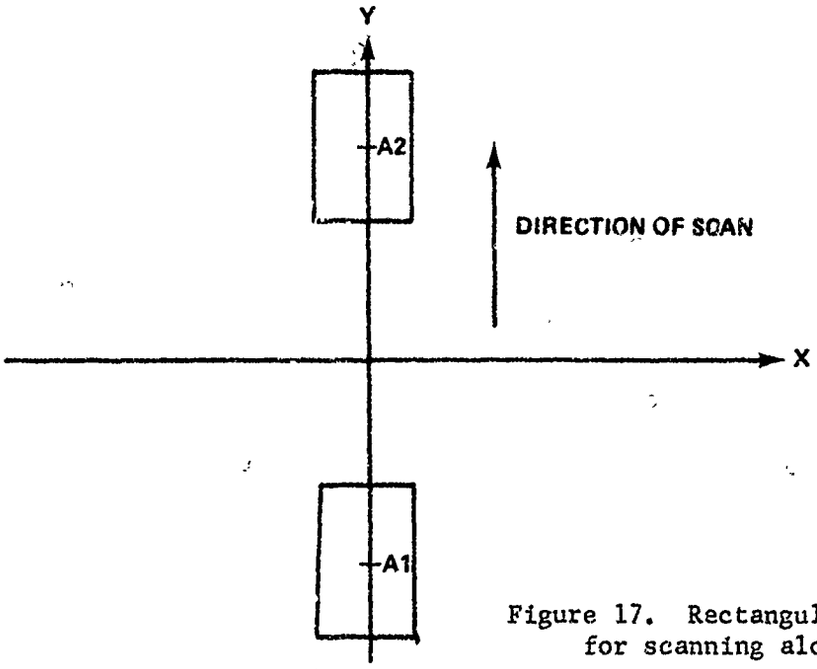


Figure 17. Rectangular aperture used for scanning along Y-axis.

Note that here the scanning rectangle maintains the same orientation with respect to the coordinate axes as it had in the X-axis scan. The user may alter this orientation by inserting a ROTATE card, which will make SS2 = SS1 and SS1 = SS2; that is, the scanning rectangle will be rotated through 90° (Figure 18).

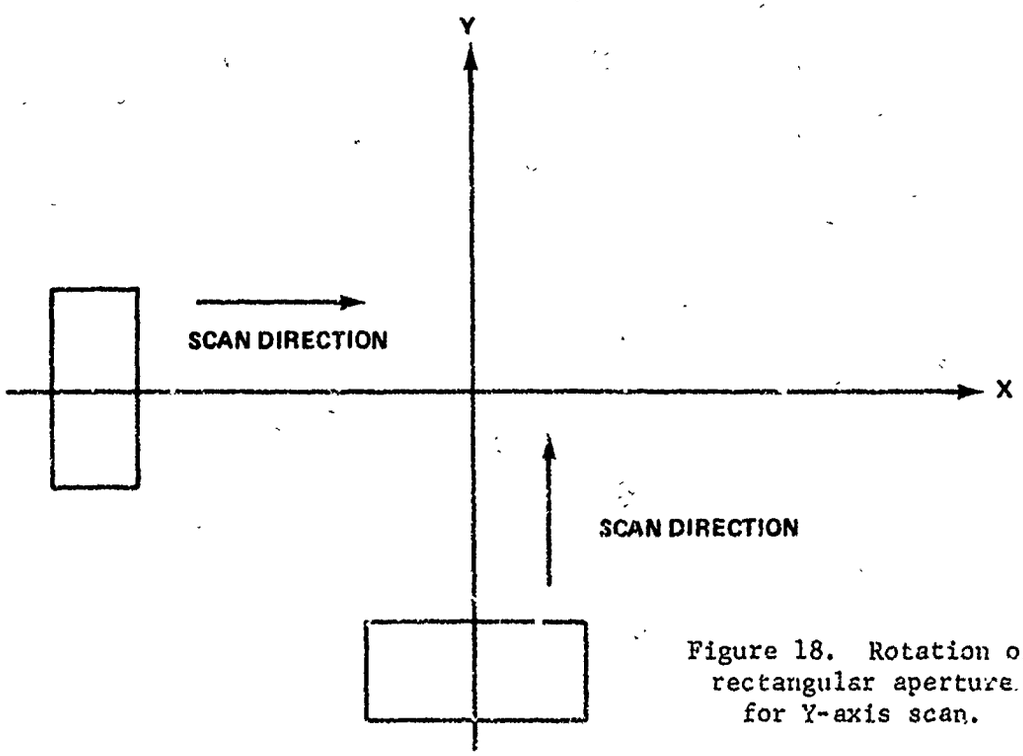


Figure 18. Rotation of rectangular aperture for Y-axis scan.

The scan then proceeds in the same manner presented for the X-axis scanning process, utilizing the appropriate Y-axis parameters in place of the X-axis parameters previously mentioned.

4. Input and Output Description

a. Input

The coordinates (X_i, Y_i) and N have been previously computed by the program and are now stored in COMMON. The data cards to be supplied by the user are, in this order:

1) A card utilizing an (I10, 6F10.0, A6) format on which are punched the values for NS, SS1, SS2, R, YTR, XTR, TILT, and the KEY, in the order given. Note that if KEY = CIRCLE and an R value is specified, this will override any SS1 and SS2 values entered. If a circular aperture is not desired, R and KEY fields are blank, and values for SS1 and SS2 are entered. If the centroid is the desired scan center, YTR = XTR = 0. TILT is the angle θ, in degrees, through which the coordinate axes are to be rotated, if desired.

2) A card utilizing a (2F10.0) format on which are punched the values for A1 and A2.

3) A card utilizing an (A6) format on which is punched ROTATE if the Y-axis scan is to use the rectangular aperture rotated through 90°. Otherwise, a blank card is inserted.

4) A card utilizing an (F10.0, 2I10) format on which are punched the values for DX, the X increment to be used for spacing tics on the plotter chart axis, N, which specifies which tics are to be emphasized and labeled, and NCHRS, which specifies the number of characters in the label.

b. Output

This subroutine provides a hard copy output of the following:

1) An echo of the data on cards 1 through 3 described in input above.

2) A columnar listing of each XC value, the number of rays enclosed by the aperture with center at XC, and the normalized value of this number (that is, the intensity). There are NS of these values.

3) A columnar listing of each YC value, the number of rays enclosed by the aperture with center at YC, and the intensity. There are NC of these values.

4) The values DX, N, and NCHRS specified in card 4 in input above. Also provided is a plot of intensity versus XC and YC values via the SC 4020 plotter.

E. Example Case Input and Output

The Cooke triplet raytrace data which were punched out by TOLDP are used as part of the input deck for the Image Analysis Program. The complete input data deck for this case is listed in Table 2, the output from the line printer is listed in Table 3, and the graphs from the SC 4020 are listed in Figures 19 through 28.

TABLE 2. INPUT DECK TO THE IMAGE ANALYSIS PROGRAM FOR THE EXAMPLE CASE

```
ON-AXIS OBJECT      EXAMPLE CASE
  15.
  .1521808E+00-.1369627E+01-.1876969E+00-.9979185E-02 .8981266E-01 .9959087E+00
 -.1521808E+00-.1369627E+01-.1876969E+00 .9979185E-02 .8981266E-01 .9959087E+00
  .1513267E+00-.1059287E+01-.1123314E+00-.9993353E-02 .6995347E-01 .9975002E+00
 -.1513267E+00-.1059287E+01-.1123314E+00 .9993353E-02 .6995347E-01 .9975002E+00
  .1507208E+00-.7536039E+00-.5763626E-01-.9993003E-02 .4996501E-01 .9987010E+00
 -.1507208E+00-.7536039E+00-.5763626E-01 .9993003E-02 .4996501E-01 .9987010E+00
  .1503318E+00-.4509955E+00-.2197705E-01-.9988501E-02 .2996550E-01 .9995010E+00
 -.1503318E+00-.4509955E+00-.2197705E-01 .9988501E-02 .2996550E-01 .9995010E+00
  .1501416E+00-.1501416E+00-.4376801E-02-.9985129E-02 .9985129E-02 .9999003E+00
 -.1501416E+00-.1501416E+00-.4376801E-02 .9985129E-02 .9985129E-02 .9999003E+00
  .1501416E+00 .1501416E+00-.4376801E-02-.9985129E-02-.9985129E-02 .9999003E+00
 -.1501416E+00 .1501416E+00-.4376801E-02 .9985129E-02-.9985129E-02 .9999003E+00
  .1503318E+00 .4509955E+00-.2197705E-01-.9988501E-02-.2996550E-01 .9995010E+00
 -.1503318E+00 .4509955E+00-.2197705E-01 .9988501E-02-.2996550E-01 .9995010E+00
  .1507208E+00 .7536039E+00-.5763626E-01-.9993003E-02-.4996501E-01 .9987010E+00
 -.1507208E+00 .7536039E+00-.5763626E-01 .9993003E-02-.4996501E-01 .9987010E+00
  .1513267E+00 .1059287E+01-.1123314E+00-.9993353E-02-.6995347E-01 .9975002E+00
 -.1513267E+00 .1059287E+01-.1123314E+00 .9993353E-02-.6995347E-01 .9975002E+00
  .1521808E+00 .1369627E+01-.1876969E+00-.9979185E-02-.8981266E-01 .9959087E+00
 -.1521808E+00 .1369627E+01-.1876969E+00 .9979185E-02-.8981266E-01 .9959087E+00
  .4558046E+00-.1215479E+01-.1662033E+00-.2995528E-01 .7988075E-01 .9963542E+00
 -.4558046E+00-.1215479E+01-.1662033E+00 .2995528E-01 .7988075E-01 .9963542E+00
  .4535943E+00-.9071886E+00-.1008127E+00-.2998193E-01 .5996386E-01 .9977502E+00
 -.4535943E+00-.9071886E+00-.1008127E+00 .2998193E-01 .5996386E-01 .9977502E+00
  .4520884E+00-.6027845E+00-.5538921E-01-.2997844E-01 .3997126E-01 .9987510E+00
 -.4520884E+00-.6027845E+00-.5538921E-01 .2997844E-01 .3997126E-01 .9987510E+00
  .4512116E+00-.3008078E+00-.2861604E-01-.2996874E-01 .1997916E-01 .9993511E+00
 -.4512116E+00-.3008078E+00-.2861604E-01 .2996874E-01 .1997916E-01 .9993511E+00
  .4509237E+000.            -.1976880E-01-.2996436E-010.            .9995510E+00
 -.4509237E+000.            -.1976880E-01 .2996436E-010.            .9995510E+00
  .4512116E+00 .3008078E+00-.2861604E-01-.2996874E-01-.1997916E-01 .9993511E+00
 -.4512116E+00 .3008078E+00-.2861604E-01 .2996874E-01-.1997916E-01 .9993511E+00
  .4520884E+00 .6027845E+00-.5538921E-01-.2997844E-01-.3997126E-01 .9987510E+00
 -.4520884E+00 .6027845E+00-.5538921E-01 .2997844E-01-.3997126E-01 .9987510E+00
  .4535943E+00 .9071886E+00-.1008127E+00-.2998193E-01-.5996386E-01 .9977502E+00
 -.4535943E+00 .9071886E+00-.1008127E+00 .2998193E-01-.5996386E-01 .9977502E+00
  .4558046E+00 .1215479E+01-.1662033E+00-.2995528E-01-.7988075E-01 .9963542E+00
 -.4558046E+00 .1215479E+01-.1662033E+00 .2995528E-01-.7988075E-01 .9963542E+00
  .7598099E+00-.1063734E+01-.1685797E+00-.4992258E-01 .6989161E-01 .9963046E+00
 -.7598099E+00-.1063734E+01-.1685797E+00 .4992258E-01 .6989161E-01 .9963046E+00
  .7566333E+00-.7566333E+00-.1123314E+00-.4996677E-01 .4996677E-01 .9975002E+00
 -.7566333E+00-.7566333E+00-.1123314E+00 .4996677E-01 .4996677E-01 .9975002E+00
  .7545982E+00-.4527589E+00-.7570298E-01-.4997015E-01 .2998209E-01 .9983006E+00
 -.7545982E+00-.4527589E+00-.7570298E-01 .4997015E-01 .2998209E-01 .9983006E+00
  .7536039E+00-.1507208E+00-.5763626E-01-.4996501E-01 .9993003E-02 .9987010E+00
 -.7536039E+00-.1507208E+00-.5763626E-01 .4996501E-01 .9993003E-02 .9987010E+00
  .7536039E+00 .1507208E+00-.5763626E-01-.4996501E-01-.9993003E-02 .9987010E+00
 -.7536039E+00 .1507208E+00-.5763626E-01 .4996501E-01-.9993003E-02 .9987010E+00
  .7545982E+00 .4527589E+00-.7570298E-01-.4997015E-01-.2998209E-01 .9983006E+00
 -.7545982E+00 .4527589E+00-.7570298E-01 .4997015E-01-.2998209E-01 .9983006E+00
  .7566333E+00 .7566333E+00-.1123314E+00-.4996677E-01-.4996677E-01 .9975002E+00
 -.7566333E+00 .7566333E+00-.1123314E+00 .4996677E-01-.4996677E-01 .9975002E+00
  .7598099E+00 .1063734E+01-.1685797E+00-.4992258E-01-.6989161E-01 .9963046E+00
 -.7598099E+00 .1063734E+01-.1685797E+00 .4992258E-01-.6989161E-01 .9963046E+00
  .1065847E+01-.9135832E+00-.1949153E+00-.6983792E-01 .5986108E-01 .9957607E+00
 -.1065847E+01-.9135832E+00-.1949153E+00 .6983792E-01 .5986108E-01 .9957607E+00
  .1062041E+01-.6068805E+00-.1472964E+00-.6992320E-01 .3995611E-01 .9967519E+00
 -.1062041E+01-.6068805E+00-.1472964E+00 .6992320E-01 .3995611E-01 .9967519E+00
```

TABLE 2. CONTINUED

```
 .1059831E+01-.3028088E+00-.1192749E+00-.6994952E-01 .1998558E-01 .9973503E+00
-.1059831E+01-.3028088E+00-.1192749E+00 .6994952E-01 .1998558E-01 .9973503E+00
 .1059106E+01-.5375286E-14-.1100223E+00-.6995456E-01 .3550408E-15 .9975502E+00
-.1059106E+01-.5375286E-14-.1100223E+00 .6995456E-01 .3550408E-15 .9975502E+00
 .1059831E+01 .3028088E+00-.1192749E+00-.6994952E-01-.1998558E-01 .9973503E+00
-.1059831E+01 .3028088E+00-.1192749E+00 .6994952E-01-.1998558E-01 .9973503E+00
 .1062041E+01 .6068804E+00-.1472964E+00-.6992320E-01-.3995611E-01 .9967519E+00
-.1062041E+01 .6068804E+00-.1472964E+00 .6992320E-01-.3995611E-01 .9967519E+00
 .1065847E+01 .9135832E+00-.1949153E+00-.6983792E-01-.5986108E-01 .9957607E+00
-.1065847E+01 .9135832E+00-.1949153E+00 .6983792E-01-.5986108E-01 .9957607E+00
 .1371631E+01-.4572104E+00-.2070071E+00-.8975266E-01 .2991755E-01 .9955146E+00
-.1371631E+01-.4572104E+00-.2070071E+00 .8975266E-01 .2991755E-01 .9955146E+00
 .1369627E+01-.1521808E+00-.1876969E+00-.8981266E-01 .9979185E-02 .9959087E+00
-.1369627E+01-.1521808E+00-.1876969E+00 .8981266E-01 .9979185E-02 .9959087E+00
 .1369627E+01 .1521808E+00-.1876969E+00-.8981266E-01-.9979185E-02 .9959087E+00
-.1369627E+01 .1521808E+00-.1876969E+00 .8981266E-01-.9979185E-02 .9959087E+00
 .1371631E+01 .4572104E+00-.2070071E+00-.8975266E-01-.2991755E-01 .9955146E+00
-.1371631E+01 .4572104E+00-.2070071E+00 .8975266E-01-.2991755E-01 .9955146E+00
   .003      .0002            5        4
        4          3          19        .0       50.        .0       90.
      21   .0015        .0015
  - 003      .003

   .0002            5          4
OFF-AXIS OBJECT     EXAMPLE CASE
   15.
        76
 .1520931E+00-.1271356E+01-.1616261E+00-.9993026E-02 .1007445E+00 .9948621E+00
-.1520931E+00-.1271356E+01-.1616261E+00 .9993026E-02 .1007445E+00 .9948621E+00
 .1512666E+00-.9604585E+00-.9256723E-01-.1000032E-01 .8080268E-01 .9966799E+00
-.1512666E+00-.9604585E+00-.9256723E-01 .1000032E-01 .8080268E-01 .9966799E+00
 .1506829E+00-.6543430E+00-.4393874E-01-.9996231E-02 .6078204E-01 .9981010E+00
-.1506829E+00-.6543430E+00-.4393874E-01 .9996231E-02 .6078204E-01 .9981010E+00
 .1503133E+00-.3514519E+00-.1419798E-01-.9989713E-02 .4077319E-01 .9991185E+00
-.1503133E+00-.3514519E+00-.1419798E-01 .9989713E-02 .4077319E-01 .9991185E+00
 .1501411E+00-.5047470E-01-.2435256E-02-.9985179E-02 .2079277E-01 .9997339E+00
-.1501411E+00-.5047470E-01-.2435256E-02 .9985179E-02 .2079277E-01 .9997339E+00
 .1501590E+00 .2497703E+00-.8248297E-02-.9984237E-02 .8263589E-03 .9999498E+00
-.1501590E+00 .2497703E+00-.8248297E-02 .9984237E-02 .8263589E-03 .9999498E+00
 .1503679E+00 .5504273E+00-.3169106E-01-.9986319E-02-.1914565E-01 .9997668E+00
-.1503679E+00 .5504273E+00-.3169106E-01 .9986319E-02-.1914565E-01 .9997668E+00
 .1507777E+00 .8526880E+00-.7328099E-01-.9988529E-02-.3912548E-01 .9991844E+00
-.1507777E+00 .8526880E+00-.7328099E-01 .9988529E-02-.3912548E-01 .9991844E+00
 .1514082E+00 .1157890E+01-.1340681E+00-.9984653E-02-.5906734E-01 .9982041E+00
-.1514082E+00 .1157890E+01-.1340681E+00 .9984653E-02-.5906734E-01 .9982041E+00
 .1522941E+00 .1467659E+01-.2157906E+00-.9962789E-02-.7882199E-01 .9968389E+00
-.1522941E+00 .1467659E+01-.2157906E+00 .9962789E-02-.7882199E-01 .9968389E+00
 .4555799E+00-.1117147E+01-.1432360E+00-.2998824E-01 .9077401E-01 .9954199E+00
-.4555799E+00-.1117147E+01-.1432360E+00 .2998824E-01 .9077401E-01 .9954199E+00
 .4534455E+00-.8083599E+00-.8404650E-01-.2999840E-01 .7079805E-01 .9970395E+00
-.4534455E+00-.8083599E+00-.8404650E-01 .2999840E-01 .7079805E-01 .9970395E+00
 .4520028E+00-.5035956E+00-.4462838E-01-.2998582E-01 .5078356E-01 .9982594E+00
-.4520028E+00-.5035956E+00-.4462838E-01 .2998582E-01 .5078356E-01 .9982594E+00
 .4511829E+00-.2014150E+00-.2374495E-01-.2997095E-01 .3078615E-01 .9990766E+00
-.4511829E+00-.2014150E+00-.2374495E-01 .2997095E-01 .3078615E-01 .9990766E+00
 .4509494E+00 .9943478E-01-.2073429E-01-.2996305E-01 .1080872E-01 .9994926E+00
-.4509494E+00 .9943478E-01-.2073429E-01 .2996305E-01 .1080872E-01 .9994926E+00
 .4512924E+00 .4001250E+00-.3542068E-01-.2996372E-01-.9164072E-02 .9995090E+00
-.4512924E+00 .4001250E+00-.3542068E-01 .2996372E-01-.9164072E-02 .9995090E+00
 .4522295E+00 .7018298E+00-.6809249E-01-.2996766E-01-.2914142E-01 .9991260E+00
```

TABLE 2. CONCLUDED

```
-.4522295E+00 .7018288E+00-.6809249E-01 .2996765E-01-.2914142E-01 .9991260E+00
 .4538045E+00 .1005818E+01-.1195405E+00-.2996089E-01-.4909966E-01 .9983444E+00
-.4538045E+00 .1005818E+01-.1195405E+00 .2996089E-01-.4909966E-01 .9983444E+00
 .4561005E+00 .1313580E+01-.1911707E+00-.2991577E-01-.6893921E-01 .9971722E+00
-.4561005E+00 .1313580E+01-.1911707E+00 .2991577E-01-.6893921E-01 .9971722E+00
 .7594861E+00-.9656053E+00-.1485931E+00-.4997112E-01 .8076728E-01 .9954795E+00
-.7594861E+00-.9656053E+00-.1485931E+00 .4997112E-01 .8076728E-01 .9954795E+00
 .7564306E+00-.6580774E+00-.9848870E-01-.4999118E-01 .6079517E-01 .9968976E+00
-.7564306E+00-.6580774E+00-.9848870E-01 .4999118E-01 .6079517E-01 .9968976E+00
 .7544993E+00-.3539207E+00-.6784212E-01-.4998058E-01 .4079317E-01 .9979168E+00
-.7544993E+00-.3539207E+00-.6784212E-01 .4998058E-01 .4079317E-01 .9979168E+00
 .7536009E+00-.5175816E-01-.5566978E-01-.4996644E-01 .2080070E-01 .9985343E+00
-.7536009E+00-.5175816E-01-.5566978E-01 .4996644E-01 .2080070E-01 .9985343E+00
 .7536957E+00 .2496458E+00-.6153815E-01-.4995874E-01 .8189224E-03 .9987509E+00
-.7536957E+00 .2496458E+00-.6153815E-01 .4995874E-01 .8189224E-03 .9987509E+00
 .7547896E+00 .5514903E+00-.8550572E-01-.4995416E-01-.1915763E-01 .9985678E+00
-.7547896E+00 .5514903E+00-.8550572E-01 .4995416E-01-.1915763E-01 .9985678E+00
 .7569363E+00 .8550217E+00-.1281317E+00-.4993523E-01-.3911353E-01 .9979863E+00
-.7569363E+00 .8550217E+00-.1281317E+00 .4993523E-01-.3911353E-01 .9979863E+00
 .7602477E+00 .1161654E+01-.1905556E+00-.4986416E-01-.5897505E-01 .9970133E+00
-.7602477E+00 .1161654E+01-.1905556E+00 .4986416E-01-.5897505E-01 .9970133E+00
 .1065453E+01-.8159362E+00-.1778278E+00-.6990430E-01 .7073276E-01 .9950428E+00
-.1065453E+01-.8159362E+00-.1778278E+00 .6990430E-01 .7073276E-01 .9950428E+00
 .1051815E+01-.5088808E+00-.1363379E+00-.6995649E-01 .5078517E-01 .9962565E+00
-.1051815E+01-.5088808E+00-.1363379E+00 .6995649E-01 .5078517E-01 .9962565E+00
 .1059754E+01-.2046054E+00-.1143113E+00-.6996175E-01 .3079913E-01 .9970741E+00
-.1059754E+01-.2046054E+00-.1143113E+00 .6996175E-01 .3079913E-01 .9970741E+00
 .1059171E+01 .9824847E-01-.1109932E+00-.6995073E-01 .1081261E-01 .9974918E+00
-.1059171E+01 .9824847E-01-.1109932E+00 .6995073E-01 .1081261E-01 .9974918E+00
 .1060040E+01 .4009432E+00-.1261842E+00-.6992908E-01-.9162515E-02 .9975099E+00
-.1060040E+01 .4009432E+00-.1261842E+00 .6992908E-01-.9162515E-02 .9975099E+00
 .1062407E+01 .7047489E+00-.1602140E+00-.6987994E-01-.2910640E-01 .9971307E+00
-.1062407E+01 .7047489E+00-.1602140E+00 .6987994E-01-.2910640E-01 .9971307E+00
 .1066400E+01 .1011053E+01-.2139903E+00-.6975823E-01-.4895381E-01 .9963620E+00
-.1066400E+01 .1011053E+01-.2139903E+00 .6975823E-01-.4895381E-01 .9963620E+00
 .1371416E+01-.3600639E+00-.1989272E+00-.8979546E-01 .4075552E-01 .9951260E+00
-.1371416E+01-.3600639E+00-.1989272E+00 .8979546E-01 .4075552E-01 .9951260E+00
 .1369617E+01-.5490982E-01-.1856659E+00-.8982175E-01 .2080345E-01 .9957406E+00
-.1369617E+01-.5490982E-01-.1856659E+00 .8982175E-01 .2080345E-01 .9957406E+00
 .1369818E+01 .2494197E+00-.1916838E+00-.8979152E-01 .8503990E-03 .9959602E+00
-.1369818E+01 .2494197E+00-.1916838E+00 .8979152E-01 .8503990E-03 .9959602E+00
 .1372035E+01 .5542642E+00-.2170540E+00-.8969610E-01-.1906269E-01 .9957867E+00
-.1372035E+01 .5542642E+00-.2170540E+00 .8969610E-01-.1906269E-01 .9957867E+00
   .003      .0002            5          4
        4          3          19          .0       50.        .0       90.
      21   .0015       .0015
  -.003      .003

   .0002            5          4
```

TABLE 3. LINE PRINTER OUTPUT FROM IMAGE ANALYSIS PROGRAM FOR EXAMPLE CASE

ON-AXIS OBJECT EXAMPLE CASE

IMAGE PLANE DISTANCE .1533333E+12

X AVERAGE 0.		Y AVERAGE 0.
-.2665301E-05	.2411146E-04	0.
.2665301E-05	.2411146E-04	0.
-.7463539E-04	.5223326E-03	0.
.7463539E-04	-.5223326E-03	0.
.5407961E-04	-.2703734E-03	0.
-.5407961E-04	-.2703734E-03	0.
.2098564E-03	-.6297142E-03	0.
-.2098564E-03	-.6297142E-03	0.
.3068235E-03	-.3068235E-03	0.
-.3068235E-03	-.3068235E-03	0.
.3068235E-03	.3068235E-03	0.
-.3068235E-03	-.3068235E-03	0.
.2098564E-03	.6297142E-03	0.
-.2098564E-03	.6297142E-03	0.
.5407961E-04	.2703734E-03	0.
-.5407961E-04	-.2703734E-03	0.
-.7463539E-04	-.5223326E-03	0.
.7463539E-04	-.5223326E-03	0.
-.2665301E-05	-.2411146E-04	0.
.2665301E-05	-.2411146E-04	0.
-.1656427E-03	.4416979E-03	0.
.1656427E-03	.4416979E-03	0.
-.1781065E-03	.3562129E-03	0.
.1781065E-03	.3562129E-03	0.
.1968929E-03	-.2490567E-03	0.
-.1968929E-03	-.2490567E-03	0.
.5304663E-03	-.3537109E-03	0.
-.5304663E-03	-.3537109E-03	0.
.6637739E-03	0.	0.
-.6637739E-03	0.	0.
.5304663E-03	.3537109E-03	0.
-.5304663E-03	.3537109E-03	0.
.1968929E-03	.2490567E-03	0.
-.1968929E-03	.2490567E-03	0.
-.1781065E-03	-.3562129E-03	0.
.1781065E-03	-.3562129E-03	0.
-.1656427E-03	-.4416979E-03	0.
.1656427E-03	-.4416979E-03	0.
-.2534717E-03	.3546900E-03	0.
.2534717E-03	.3546900E-03	0.
-.3734527E-03	.3734527E-03	0.
.3734527E-03	.3734527E-03	0.
-.1933631E-04	.1162178E-04	0.
.1933631E-04	.1162178E-04	0.
.2703734E-03	-.5407961E-04	0.
-.2703734E-03	-.5407961E-04	0.
.2703734E-03	.5407961E-04	0.
-.2703734E-03	.5407961E-04	0.
-.1933631E-04	-.1162178E-04	0.
.1933631E-04	-.1162178E-04	0.
-.3734527E-03	-.3734527E-03	0.
.3734527E-03	-.3734527E-03	0.
-.2534717E-03	-.3546900E-03	0.
.2534717E-03	-.3546900E-03	0.
.1679327E-03	-.1267437E-03	0.
-.1679327E-03	-.1267437E-03	0.

TABLE 3. CONTINUED

-.5578630E-03	.3188852E-03	0.
.5578630E-03	.3188852E-03	0.
-.5647526E-03	.1614583E-03	0.
.5647526E-03	-.1614583E-03	0.
-.5047961E-03	.2563060E-17	0.
.5047961E-03	-.2563060E-17	0.
-.5647526E-03	-.1614583E-03	0.
.5647526E-03	.1614583E-03	0.
-.5578630E-03	-.3188852E-03	0.
.5578630E-03	.3188852E-03	0.
.1479027E-03	.1267437E-03	0.
-.1479027E-03	-.1267437E-03	0.
.6120939E-03	-.2941489E-03	0.
-.6120939E-03	.2941489E-03	0.
-.2411146E-04	.2665301E-05	0.
.2411146E-04	-.2665301E-05	0.
-.2411146E-04	-.2665301E-05	0.
.2411146E-04	.2665301E-05	0.
.6120939E-03	.2941489E-03	0.
-.6120939E-03	-.2941489E-03	0.

PLOT SIZE	TIC SPACING	TIC EMPHASIZED	TIC CHARACTERS
.5333333E-02	.2333333E-03	5	

NFREQ= 19 STARTING FREQ= 0.0000 DELTA FREQ= 50.0000 TARGET ORIENTATION= 0.0000

TIC EMPHASIS= 5 TIC CHARACTERS= .

FREQUENCY	MTF	PHASE ANGLE
0.000	1.0000	0.0000
50.000	.9944	0.0000
100.000	.9776	0.0000
150.000	.9502	0.0000
200.000	.9124	0.0000
250.000	.8665	0.0000
300.000	.8125	0.0000
350.000	.7521	0.0000
400.000	.6869	0.0000
450.000	.6186	0.0000
500.000	.5488	0.0000
550.000	.4793	0.0000
600.000	.4116	0.0000
650.000	.3472	0.0000
700.000	.2875	0.0000
750.000	.2337	0.0000
800.000	.1866	0.0000
850.000	.1470	0.0000
900.000	.1156	0.0000

TABLE 3. CONTINUED

NFREQ= 19 STARTING FREQ= 0.0000 DELTA FREQ= 50.0000 TARGET ORIENTATION= 90.0000

TIC EMPHASIS= 4 TIC CHARACTERS= 4

FREQUENCY	MTF	PHASE ANGLE
0.000	1.0000	0.0000
50.000	.9953	-.0000
100.000	.9816	-.0000
150.000	.9596	-.0000
200.000	.9277	-.0000
250.000	.8874	-.0000
300.000	.8416	-.0000
350.000	.7895	-.0000
400.000	.7312	-.0000
450.000	.6693	-.0000
500.000	.6046	-.0000
550.000	.5377	-.0000
600.000	.4702	-.0000
650.000	.4032	-.0000
700.000	.3378	-.0000
750.000	.2745	-.0000
800.000	.2147	-.0000
850.000	.1589	-.0000
900.000	.1078	-.0000

NO. OF STRIPS= 21 APERTURE WIDTH= .1111 APERTURE WEIGHT= .0000 RADIUS= -0.0000

X TRANSLATE= -0.2750 Y TRANSLATE= -0.0000 TILT ANGLE= -0.0000 APERTURE KEY=

LEFT SCAN= -.0000 RIGHT SCAN= .0000

TABLE 3. CONTINUED

X VALUE	NO. OF RAYS	INTENSITY
-.0030	3	0.0000
-.0027	0	0.0000
-.3324	3	3.3333
-.0021	0	0.0000
-.0018	0	0.0000
-.0015	0	0.0000
-.0012	10	.1316
-.0009	26	.3421
-.0006	50	.6579
-.0003	66	.8684
-.0000	76	1.0000
.0003	66	.8684
.0006	50	.6579
.0009	26	.3421
.0012	10	.1316
.0015	0	0.0000
.0018	0	0.0000
.0021	0	0.0000
.0024	0	0.0000
.0027	0	0.0000
.0030	0	0.0000

Y VALUE	NO. OF RAYS	INTENSITY
-.0030	0	0.0000
-.0027	0	0.0000
-.0024	0	0.0000
-.0021	0	0.0000
-.0018	0	0.0000
-.0015	0	0.0000
-.0012	10	.1316
-.0009	26	.3421
-.0006	50	.6579
-.0003	72	.9474
-.0000	76	1.0000
.0003	72	.9474
.0006	50	.6579
.0009	26	.3421
.0012	10	.1316
.0015	0	0.0000
.0018	0	0.0000
.0021	0	0.0000
.0024	0	0.0000
.0027	0	0.0000
.0030	0	0.0000

TIC SPACING= .0012 TIC CHANGE/TICK= 0 CHARACTERS= 0

TABLE 3. CONTINUED

OFF-AXIS OBJECT EXAMPLE CASE

IMAGE PLANE DISTANCE .15[illegible]E+02

X AVERAGE 0. Y AVERAGE .2624471E+03

-.1998968E-03	.1485762E-02	0.
.1994460E-03	.1469762E-02	0.
-.1666755E-03	.6264992E-03	0.
.1666755E-03	.6246992E-03	0.
.1409314E-04	-.5990585E-03	0.
-.1409314E-04	-.5994585E-03	0.
.1934461E-03	-.1232149E-02	0.
-.1934486E-03	-.1232148E-02	0.
.2992256E-03	-.3465810E-03	0.
-.2992256E-03	-.3465810E-03	0.
.3855694E-03	-.3239744E-03	0.
-.3855694E-03	-.3239744E-03	0.
.2216239E-03	.7157842E-04	0.
-.2216239E-03	.7157842E-04	0.
.9489881E-04	-.3964273E-04	0.
-.9489881E-04	-.3964273E-04	0.
.2791769E-04	-.1445383E-03	0.
-.2791769E-04	-.1445383E-03	0.
.2216726E-03	.2619756E-02	0.
-.2216726E-03	.2313756E-02	0.
-.6285768E-03	.1792989E-02	0.
.6285768E-03	.1292989E-02	0.
-.3953564E-03	.2353497E-03	0.
.3953564E-03	.2353497E-03	0.
.9668323E-04	-.7417370E-03	0.
-.9668323E-04	-.7417373E-03	0.
.4938222E-03	-.7952393E-03	0.
-.4938222E-03	-.8621231E-03	0.
.6533075E-03	-.6249848E-03	0.
-.6533075E-03	-.6249848E-03	0.
.3544521E-03	-.2254633E-03	0.
-.3544521E-03	-.2254633E-03	0.
.2798227E-03	-.1562225E-03	0.
-.2798227E-03	-.1562225E-03	0.
.5938817E-04	-.2744913E-03	0.
-.5938817E-04	-.2744913E-03	0.
.3561775E-03	.8457357E-03	0.
-.3561775E-03	.8457357E-03	0.
-.9435860E-03	.3642597E-03	0.
.9435860E-03	.3642597E-03	0.
-.7896181E-03	.1972931E-03	0.
.7896181E-03	.1972931E-03	0.
-.1723234E-03	-.4695382E-03	0.
.1723234E-03	-.4695382E-03	0.
.2134466E-03	-.6271314E-03	0.
-.2134466E-03	-.6271314E-03	0.
.2991640E-03	-.5266397E-03	0.
-.2991640E-03	-.5266397E-03	0.
.1250329E-03	-.4239366E-03	0.
-.1250329E-03	-.4239366E-03	0.
-.1473815E-04	-.3439397E-03	0.
.1473815E-04	-.3439397E-03	0.
.5143094E-03	.5094356E-03	0.
-.5143094E-03	.5094356E-03	0.
-.8781973E-03	-.4476716E-03	0.

TABLE 3. CONTINUED

.4281928E-03	-.4547671E-03	0.
-.1046902E-02	.1126436E-03	0.
.2048902E-02	.2126.38E-03	0.
-.7726536E-03	-.2268332.E-03	0.
.7726636E-03	-.3268324E-03	0.
-.5119020E-03	-.4485378E-03	0.
.5119020E-03	-.4485378E-03	0.
-.3695407E-03	-.4937755E-03	0.
.3695407E-03	-.4937755E-03	0.
-.3631331E-04	-.2771979E-03	0.
.3631331E-04	-.2771979E-03	0.
.1223855E-02	.1053738E-02	0.
-.1223855E-02	.1053733E-02	0.
-.6324929E-04	-.4647626E-04	0.
.6324929E-04	-.4647626E-04	0.
-.2207731E-03	.1413142E-03	0.
.2207731E-03	-.1413142E-03	0.
.2316633E-03	-.1363371E-03	0.
-.2016488E-03	-.1046321E-03	0.
.1349493E-02	.4517635E-03	0.
-.1349493E-02	.4517635E-03	0.

PLOT SIZE	TIC SPACING	TIC EMPHASIZED	TIC CHARACTERS
.50000000E-02	.20000000E-03	5	4

NFREQ= 19 STARTING FREQ= 0.0000 DELTA FREQ= 50.0000 TARGET ORIENTATION= 0.0000

TIC EMPHASIS= 4 TIC CHARACTERS= 4

FREQUENCY	MTF	PHASE ANGLE
0.000	1.0000	0.0000
50.000	.9859	0.0000
100.000	.9487	0.0000
150.000	.8889	0.0000
200.000	.8126	0.0000
250.000	.7261	0.0000
300.000	.6360	0.0000
350.000	.5485	0.0000
400.000	.4688	0.0000
450.000	.4034	0.0000
500.000	.3449	0.0000
550.000	.3033	0.0000
600.000	.2709	0.0000
650.000	.2485	0.0000
700.000	.2307	0.0000
750.000	.2145	0.0000
800.000	.1953	0.0000
850.000	.1801	0.0000
900.000	.1593	0.0000

TABLE 3. CONTINUED

NFREQ= 19 STARTING FREQ= 0.0000 DELTA FREQ= 50.3333 TARGET ORIENTATION= 90.3333

TIC EMPHASIS= 4 TIC CHARACTERS= 4

FREQUENCY	MTF	PHASE ANGLE
3.333	1.0000	0.0000
50.000	.9755	-.0016
100.000	.9071	-.0129
1 3.000	.8055	-.0447
2 1.333	.6876	-.1196
25[illegible] 000	.5720	-.2194
300.000	.4766	-.3787
350.000	.4077	-.5726
400.000	.3619	-.7636
450.000	.3242	-.9411
500.000	.2975	-1.0876
550.000	.2674	-1.2285
600.000	.2405	-1.3500
650.000	.2232	-1.4733
700.000	.2073	1.5696
750.000	.1987	1.5334
800.000	.1901	1.4913
850.000	.1742	1.4053
900.000	.1617	1.4953

NO. OF STEPS= 21 APERTURE WIDTH= .3315 APERTURE HEIGHT= .3315 RADIUS= -0.3800

Y TRANSLATE= -0.0000 X TRANSLATE= -0.0300 TILT ANGLE= -0.0300 APERTURE KEY=

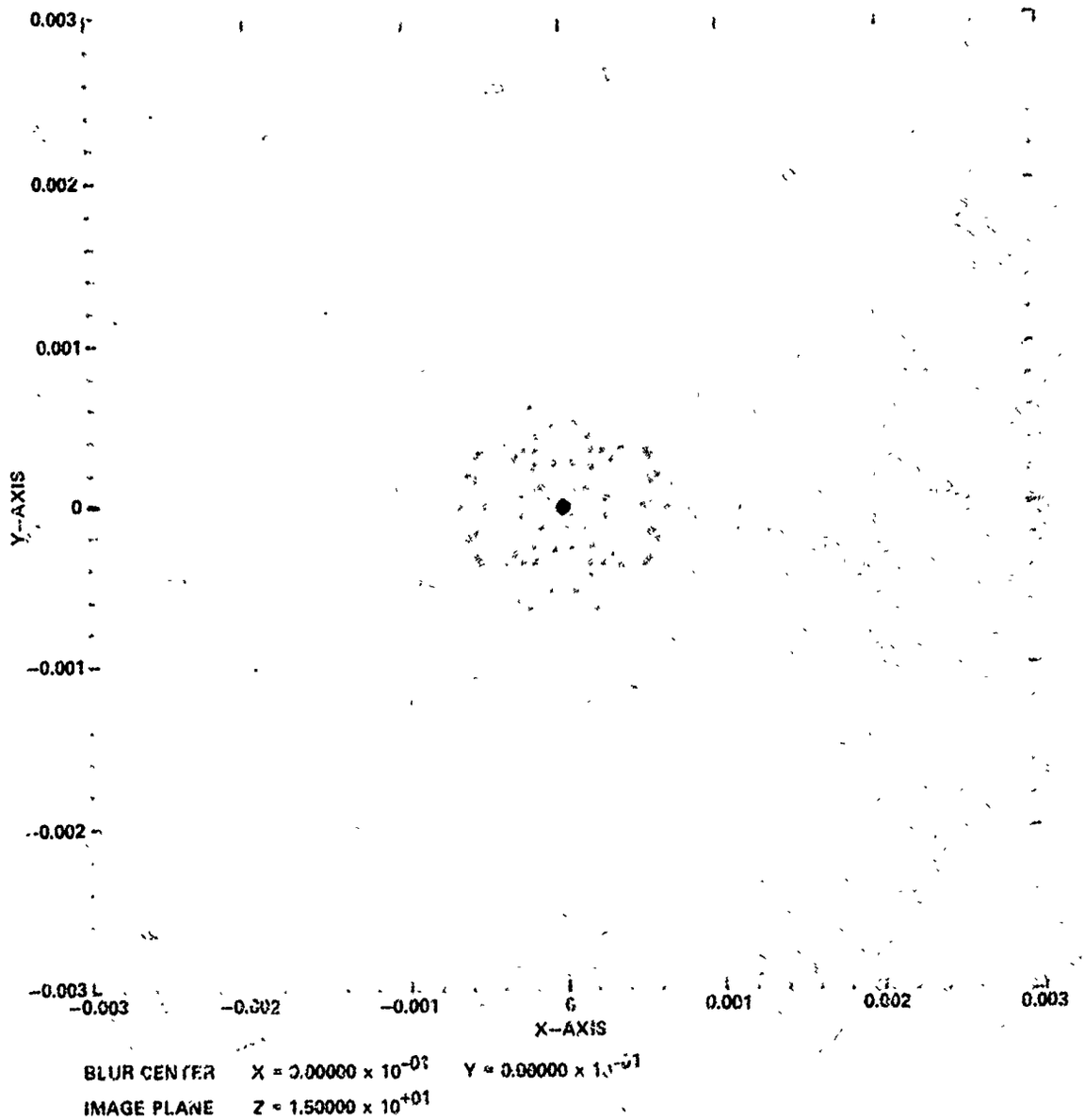
LEFT SCAN= -.0033 RIGHT SCAN= .3333

TABLE 3. CONCLUDED

X VALUE	NO. OF RAYS	INTENSITY
-.0033	3	3.0000
-.0027	3	3.0000
-.0024	3	4.0000
-.0021	3	3.0000
-.0018	1	.3333
-.0015	4	.3000
-.0012	9	.1333
-.0009	23	.4800
-.0006	36	.7633
-.0003	48	.9600
-.0000	50	1.0000
.0003	48	.9600
.0006	38	.7600
.0009	23	.4600
.0012	9	.1800
.0015	4	.0800
.0018	1	.0200
.0021	3	3.0000
.0024	3	3.0000
.0027	3	3.0000
.0030	3	3.0000

Y VALUE	NO. OF RAYS	INTENSITY
-.0033	3	3.0000
-.0027	3	3.0000
-.0024	3	3.0000
-.0021	3	3.0000
-.0018	2	.0400
-.0015	6	.1200
-.0012	15	.4000
-.0009	36	.7200
-.0006	48	.9600
-.0003	46	1.0000
-.0000	50	1.0000
.0003	38	.7600
.0006	23	.4600
.0009	14	.2800
.0012	10	.2000
.0015	8	.1600
.0018	6	.1200
.0021	4	.0800
.0024	2	.0400
.0027	2	.0400
.0030	2	3.0000

TIC SPACING= .0002 TIC EMPHASIZED= 5 CHARACTERS= 4



BLUR CENTER X = 0.00000 x 10^{-01} Y = 0.00000 x 10^{-01}

IMAGE PLANE Z = 1.50000 x 10^{+01}

Figure 19. Spot diagram for on-axis object.

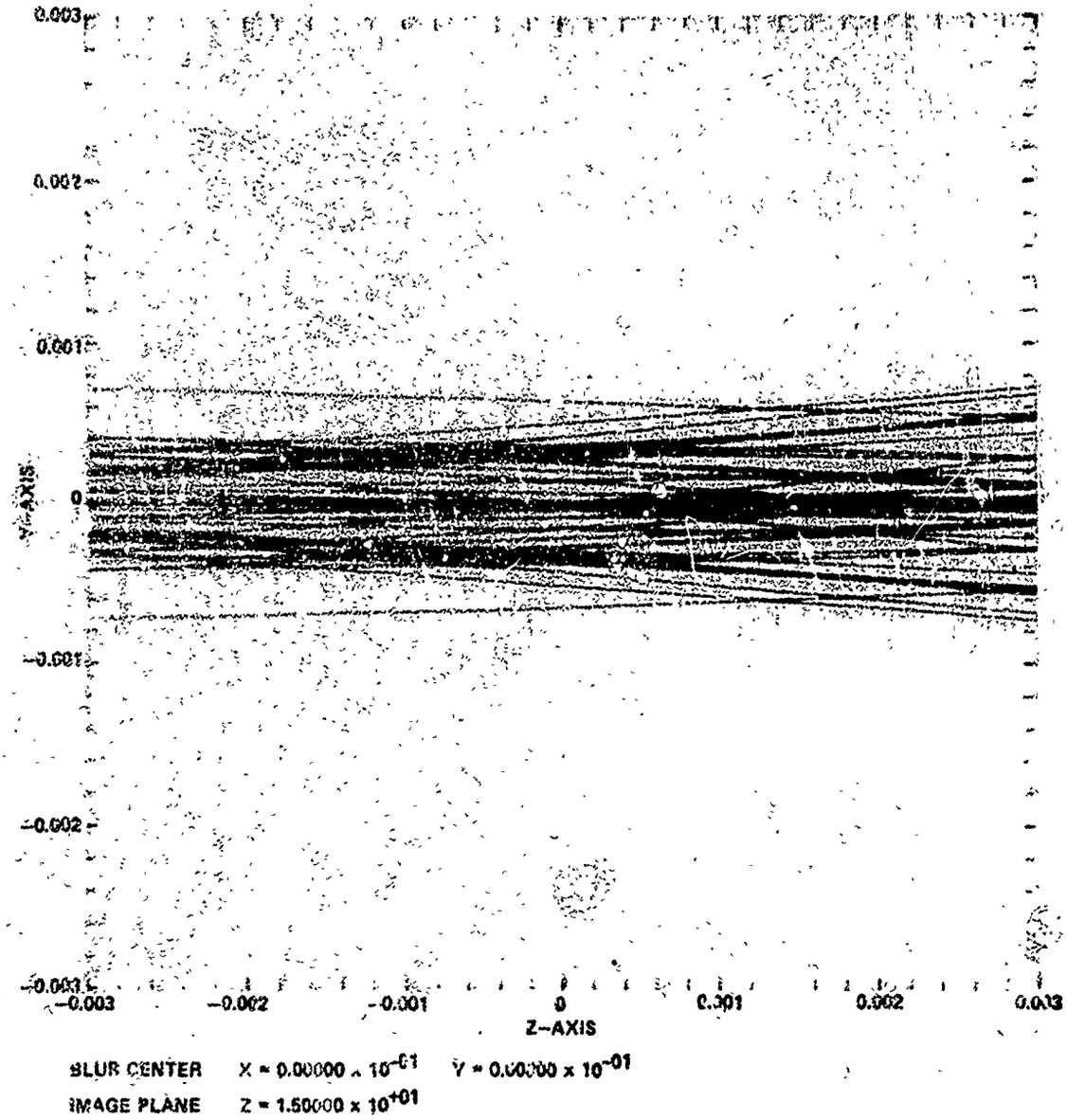


Figure 20. Y,Z ray profile for on-axis object.

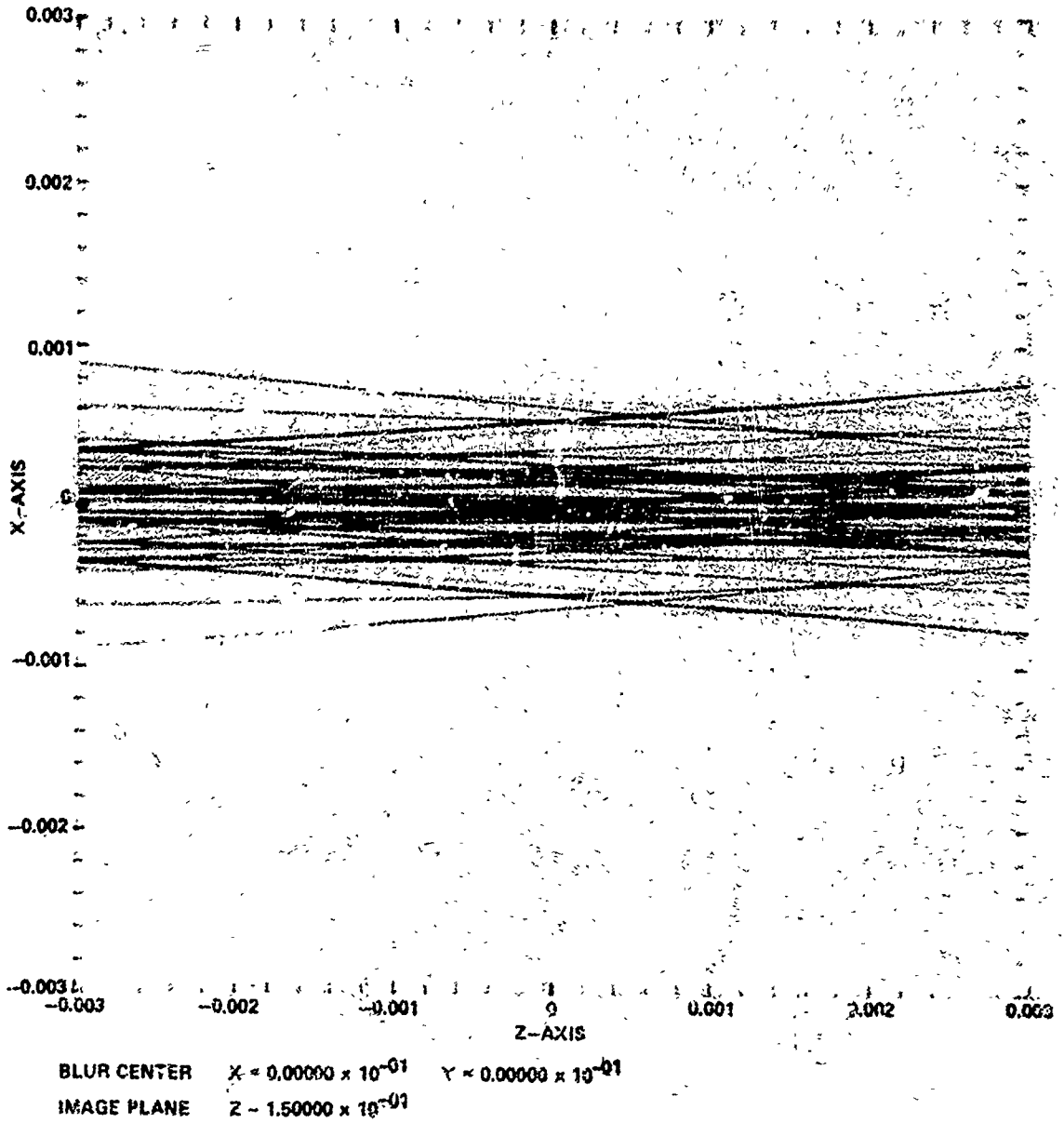


Figure 21. X,Z ray profile for on-axis object.

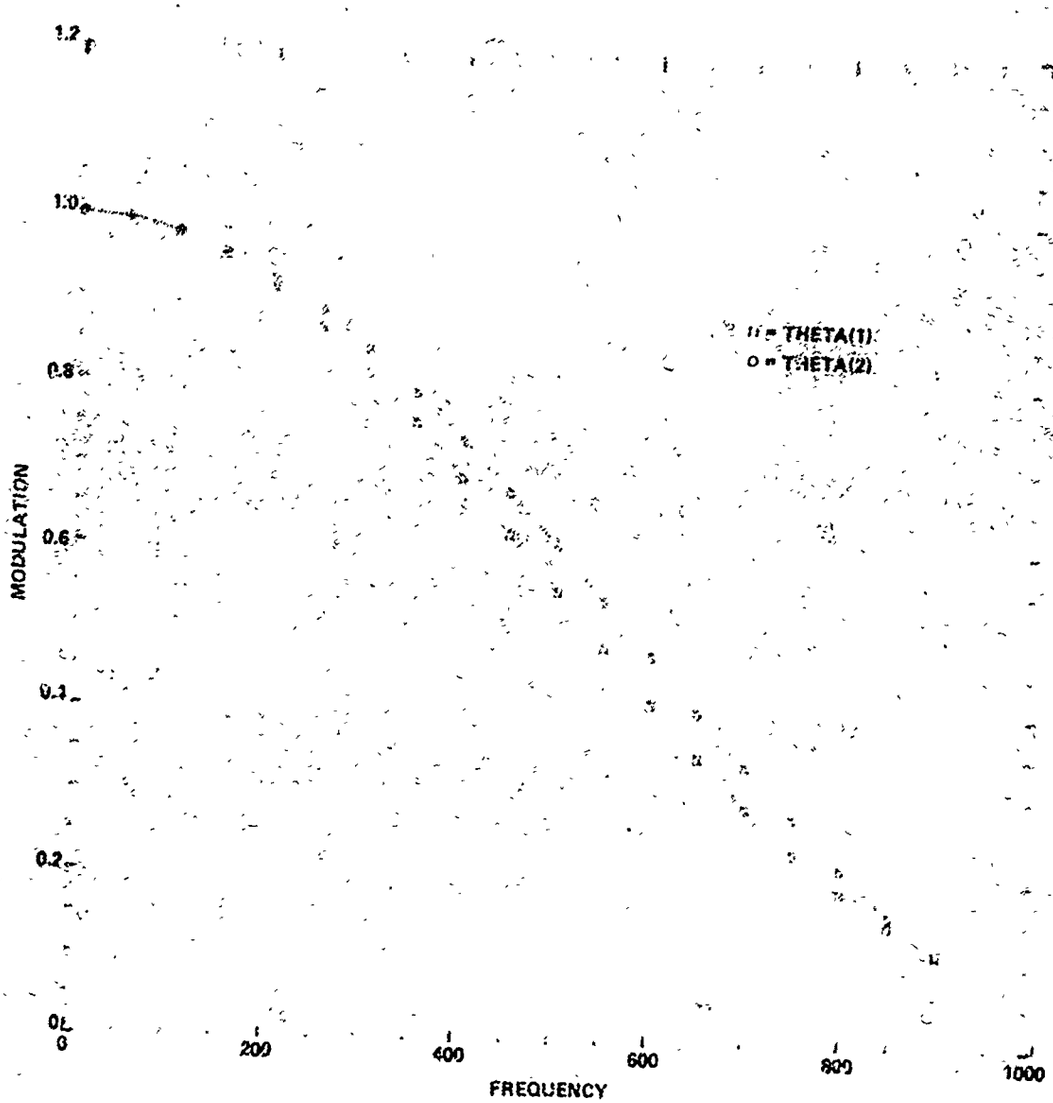


Figure 22. Modulation transfer function for on-axis object.

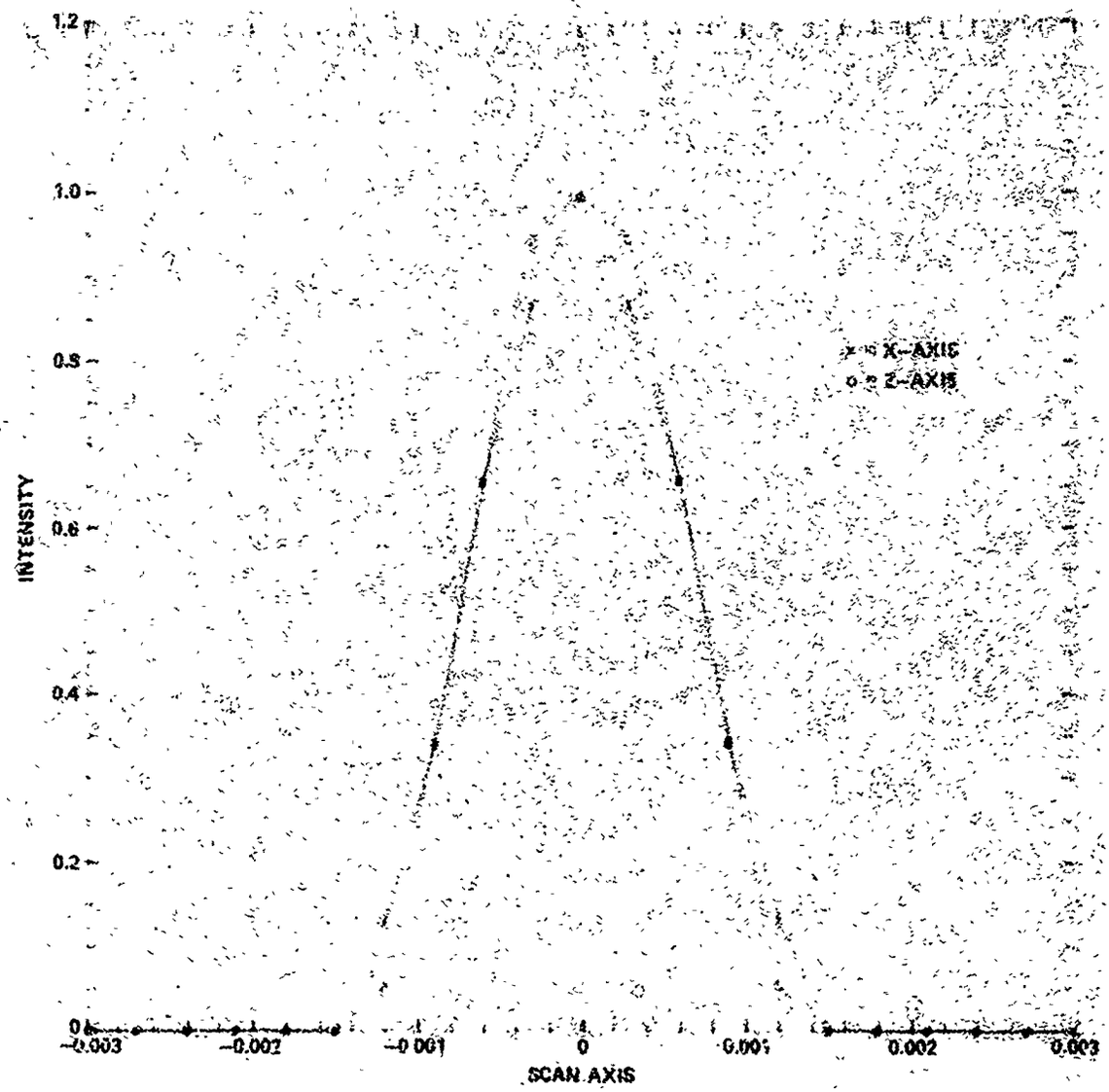
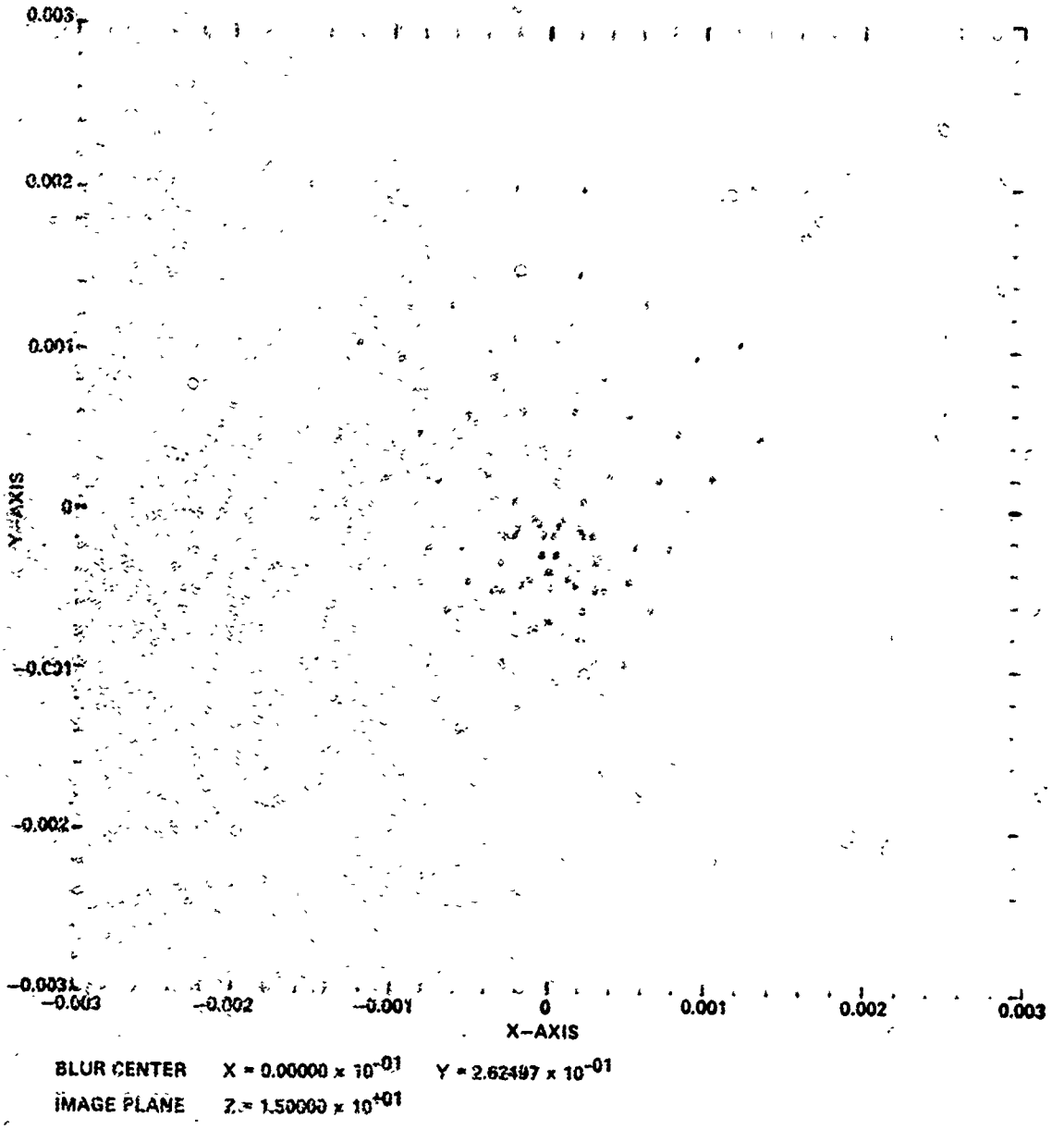


Figure 23. Aperture scans for on-axis object.



BLUR CENTER X = 0.00000 x 10^{-01} Y = 2.62497 x 10^{-01}

IMAGE PLANE Z = 1.50000 x 10^{+01}

Figure 24. Spot diagram for off-axis object.

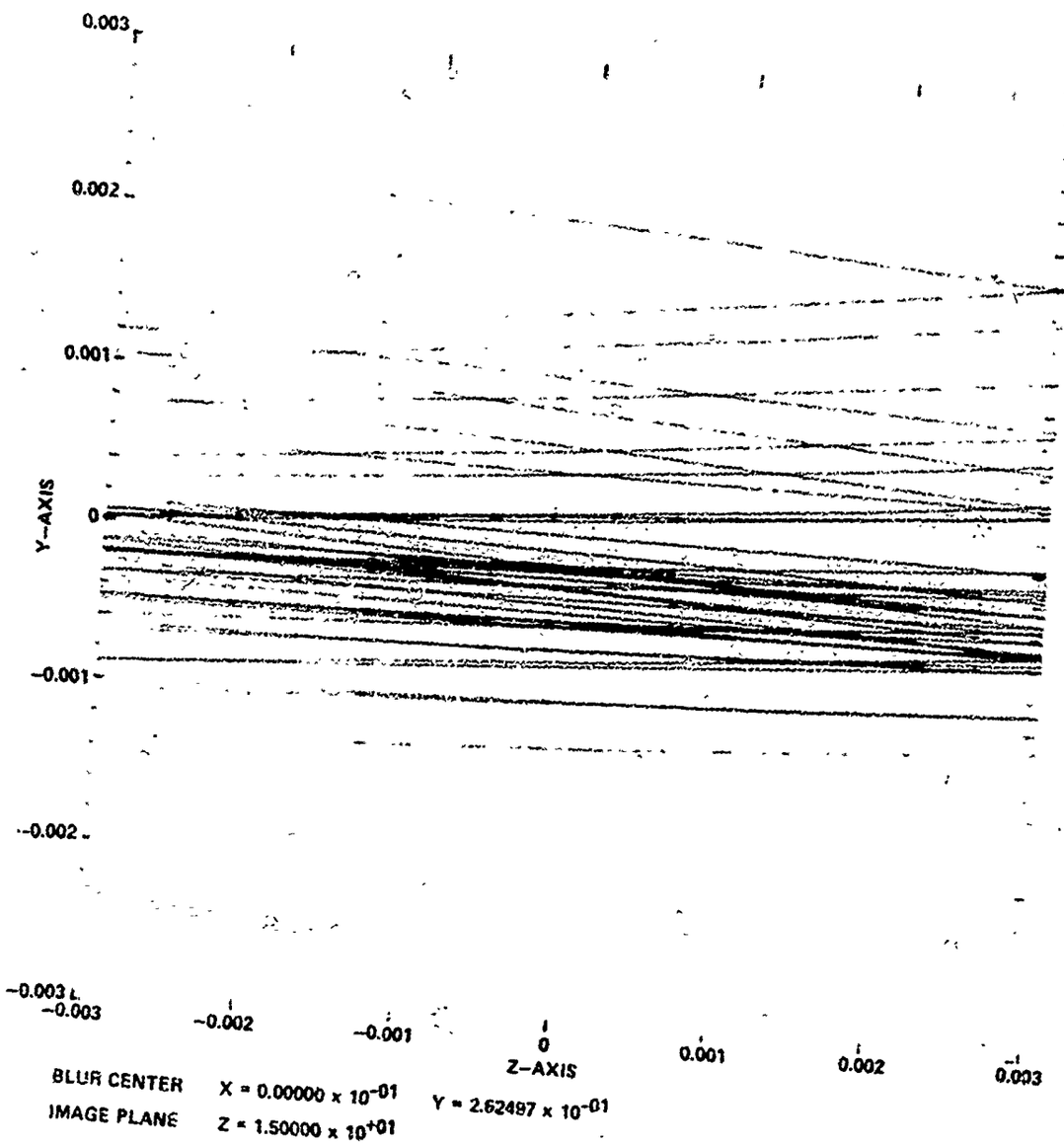
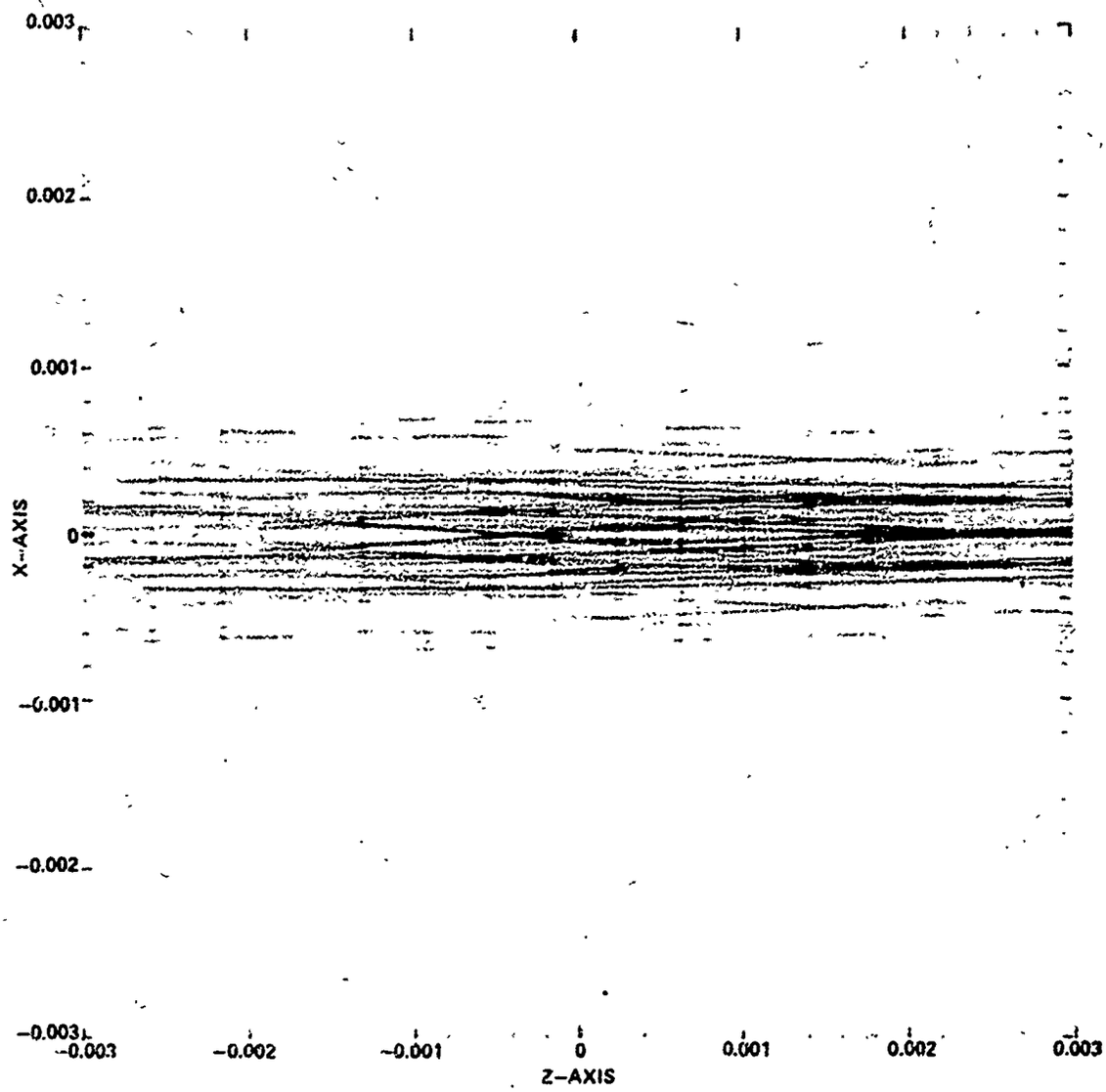


Figure 25. Y,Z ray profile for off-axis object.



BLUR CENTER X = 0.00000 x 10^{-01} Y = 2.62497 x 10^{-01}

IMAGE PLANE Z = 1.50000 x 10^{+01}

Figure 26. X,Z ray profile for off-axis object.

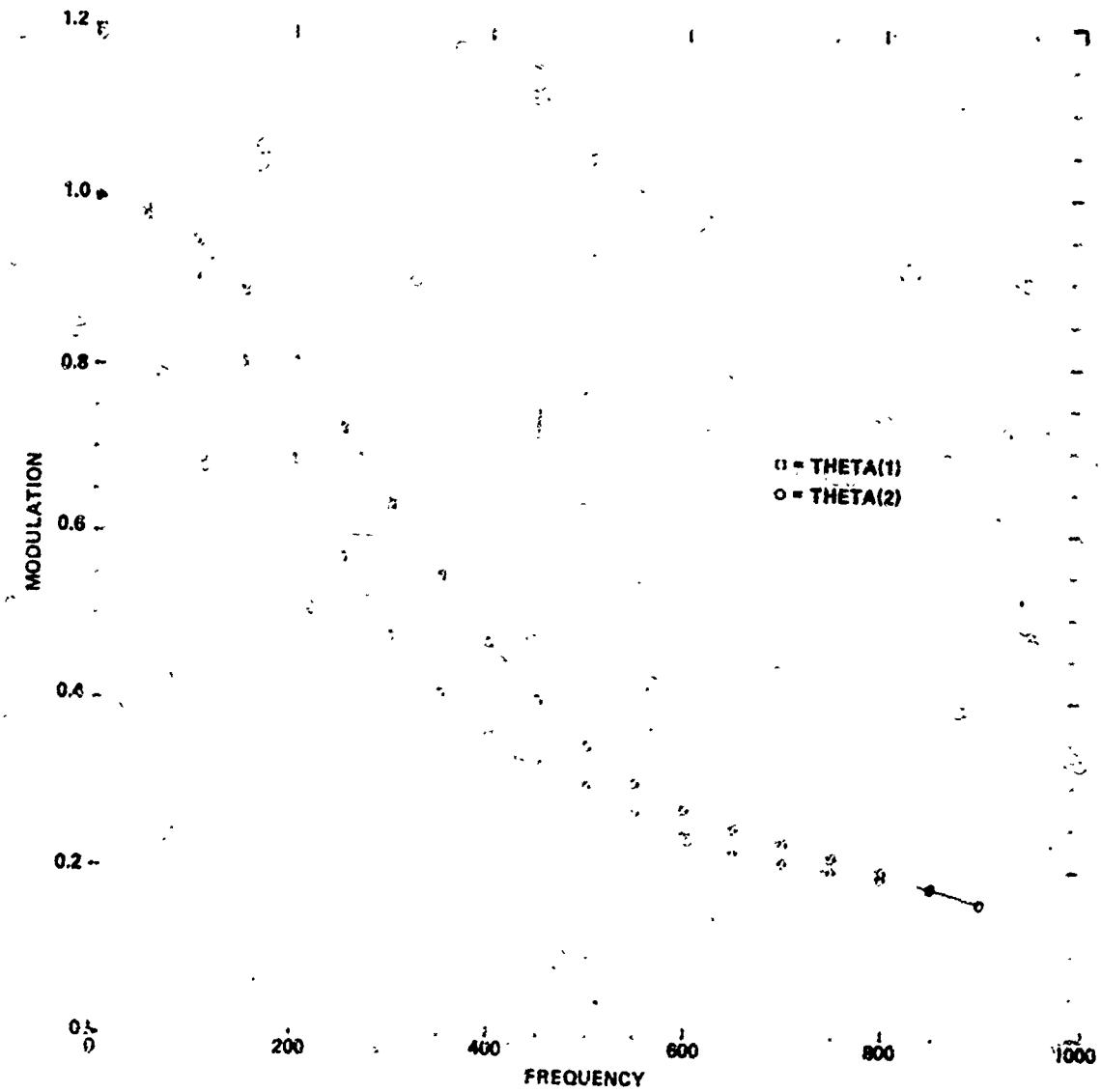


Figure 27. Modulation transfer function for off-axis object.

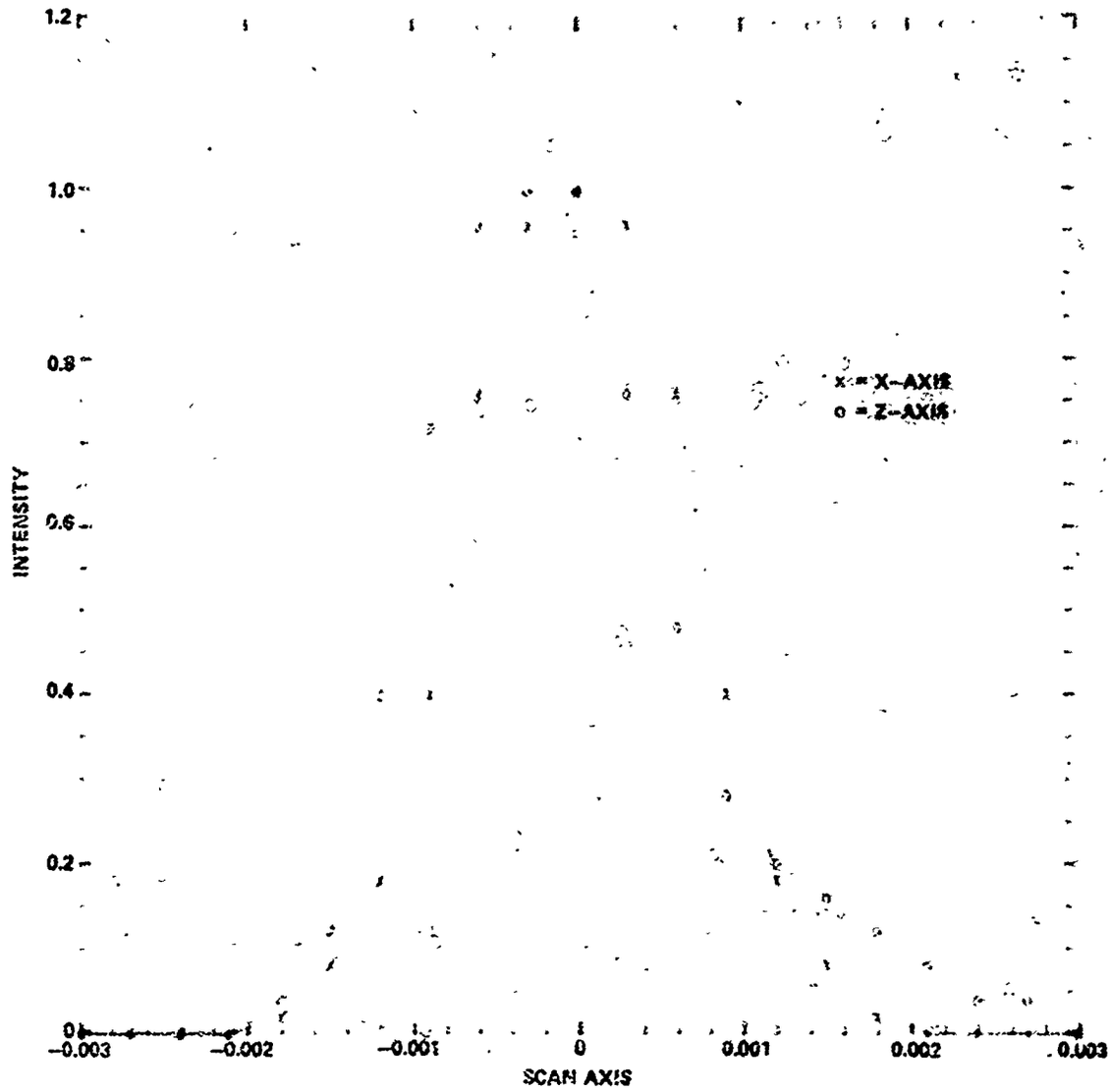


Figure 28. Aperture scans for off-axis object.

Appendix A

FORTRAN LISTING OF IMAGE ANALYSIS PROGRAM

```
      PROGRAM MAIN(INPUT,OUTPUT,FILMPL,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON/RAYS/X(201),Y(201),Z(201),QX(201),QY(201),QZ(201),
     1NPR,LABEL(6),XAVG,YAVG,DELD
      DATA ICENT/5HCENTER/
C
C     READ INPUT PARAMETERS
    1 READ(5,100)(LABEL(I),I=1,6)
      IF(EOF(5))10,11
   10 STOP
   11 CONTINUE
  100 FORMAT(6A10)
      WRITE(6,107)(LABEL(I),I=1,6)
  107 FORMAT(1H1,6A10)
C     DELD IS SIGNED DISTANCE FROM LAST SURFACE VERTEX TO IMAGE PLANE
      READ(5,102)DELD
  102 FORMAT(F10.0)
      WRITE (6,109)
      WRITE(6,108)DELD
  108 FORMAT(1H ,20HIMAGE PLANE DISTANCE,5XE13.7)
C*******************
C
C     READ DECK PUNCHED BY FOLDP
      READ(5,103)NPR
  103 FORMAT(I10)
      DO 104 I=1,NPR
  104 READ(5,105)X(I),Y(I),Z(I),QX(I),QY(I),QZ(I)
  105 FORMAT(6E13.7)
C*******************
C
C     COMPUTE COORDINATES ON IMAGE PLANE
      DO 106 I=1,NPR
      X(I)=(QX(I)/QZ(I))*(DELD-Z(I))+X(I)
      Y(I)=(QY(I)/QZ(I))*(DELD-Z(I))+Y(I)
  106 Z(I)=0.
      FNPR=NPR
      XAVG=0.
      YAVG=0.
C
C     TRANSLATE ORIGIN TO CENTER OF BLUR
      DO 201 I=1,NPR
      XAVG=XAVG+X(I)
  201 YAVG=YAVG+Y(I)
      XAVG=XAVG/FNPR
      YAVG=YAVG/FNPR
      DO 202 I=1,NPR
      X(I)=X(I)-XAVG
  202 Y(I)=Y(I)-YAVG
  205 WRITE(6,109)
  109 FORMAT(1H )
      WRITE(6,110)XAVG,YAVG
  110 FORMAT(1H ,9HX AVERAGE,5XE13.7,10X,9HY AVERAGE,5XE13.7)
      WRITE(6,109)
      DO 203 K=1,NPR
  203 WRITE(6,204)X(K),Y(K),Z(K)
  204 FORMAT(1H ,3(5XE13.7))

      CALL INITIL
      CALL RAPLOT
      CALL MTF
      CALL SCANS
      GO TO 1
      END
```

```
      SUBROUTINE RAPLOT
      COMMON/RAYS/X(201),Y(201),Z(201),QX(201),QY(201),QZ(201),
     1NPR,LABEL(5),XAVG,YAVG,DELD
C
C     READ INPUT DATA
      READ(5,103)SCALE,DELTXY,NEMPHS,NCHRS
  103 FORMAT(2F10.0,2I10)
      WRITE(6,104)
  104 FORMAT (1H1,75H        PLOT SIZE          TIC SPACING        TIC EMPH
     1ASIZED     TIC CHARACTERS)
      WRITE(6,105)SCALE,DELTXY,NEMPHS,NCHRS
  105 FORMAT(1H ,2(4XE15.8),2(15XI4))
      XLEFT=-SCALE
      XRIGHT=SCALE
C
C     DRAW X-Y PLOT
      CALL GRID(XLEFT,XRIGHT,XLEFT,XRIGHT,DELTXY,DELTXY,NEMPHS,NEMPHS,
     1NEMPHS,NEMPHS,NCHRS,NCHRS)
      CALL PRINTV(60,LABEL,270,1000)
      CALL PRINTV(-6,6HX-AXIS,530,0)
      CALL APRNTV(0,-14,-6,6HY AXIS,0,550)
      CALL APLOTV(NPR,X,Y,1,1,1,44,IERR)
      CALL PRINTV(-37,37HBLUR CENTER   X =                    Y =,100,20)
      CALL LABLV(XAVG,244,20,-6,1,1)
      CALL LABLV(YAVG,404,20,-6,1,1)
      CALL PRINTV(-17,17HIMAGE PLANE   Z =,100,0)
      CALL LABLV(DELD,244,0,-6,1,1)
C
C     DRAW Y-Z PLOT
      CALL GRID(XLEFT,XRIGHT,XLEFT,XRIGHT,DELTXY,DELTXY,NEMPHS,NEMPHS,
     1NEMPHS,NEMPHS,NCHRS,NCHRS)
      CALL PRINTV(60,LABEL,270,1030)
      CALL PRINTV(-6,6HZ-AXIS,500,0)
      CALL APRNTV(0,-14,-6,6HY AXIS,0,600)
      CALL PRINTV(-37,37HBLUR CENTER   X =                    Y =,100,20)
      CALL LABLV(XAVG,244,20,-6,1,1)
      CALL LABLV(YAVG,404,20,-6,1,1)
      CALL PRINTV(-17,17HIMAGE PLANE   Z =,100,0)
      CALL LABLV(DELD,244,0,-6,1,1)
      DO 200 I=1,NPR
      IZ1=NXV(XLEFT)
      IZ2=NXV(XRIGHT)
      YL=Y(I)+XLEFT*QY(I)/QZ(I)
      IF(ABS(YL).LE.ABS(XLEFT))GO TO 201
      ZLNEW=XLEFT*(SIGN(XLEFT,YL)-Y(I))/(YL-Y(I))
      YL=SIGN(XLEFT,YL)
      IZ2=NXV(ZLNEW)
  201 YR=Y(I)+XRIGHT*QY(I)/QZ(I)
      IF(ABS(YR).LE.ABS(XLEFT))GO TO 202
      ZRNEW=XRIGHT*(SIGN(XRIGHT,YR)-Y(I))/(YR-Y(I))
      YR=SIGN(XRIGHT,YR)
      IZ2=NXV(ZRNEW)
  202 IY1=NYV(YL)
      IY2=NYV(YR)
  200 CALL LINEV(IZ1,IY1,IZ2,IY2)
```

```
C
C     DRAW X-Z PLOT
      CALL GRID(XLEFT,XRIGHT,XLEFT,XRIGHT,DELTXY,DELTXY,NEMPHS,NEMPHS,
     1NEMPHS,NEMPHS,NCHRS,NCHRS)
      CALL PRINTV(60,LABEL,270,1000)
      CALL PRINTV(-6,6HZ-AXIS,500,0)
      CALL APRNTV(0,-14,-6,6HX AXIS,0,600)
      CALL PRINTV(-37,37HBLUR CENTER   X =                    Y =,100,20)
      CALL LABLV(XAVG,244,20,-5,1,1)
      CALL LABLV(YAVG,404,20,-6,1,1)
      CALL PRINTV(-17,17HIMAGE PLANE   Z =,100,0)
      CALL LABLV(DELD,244,0,-5,1,1)
      DO 300 I=1,NPR
      IZ1=NXV(XLEFT)
      IZ2=NXV(XRIGHT)
      XL=X(I)+XLEFT*QX(I)/QZ(I)
      IF(ABS(XL).LE.ABS(XLEFT))GO TO 301
      ZLNEW=XLEFT*(SIGN(XLEFT,XL)-X(I))/(XL-X(I))
      XL=SIGN(XLEFT,XL)
      IZ1=NXV(ZLNEW)
  301 XR=X(I)+XRIGHT*QX(I)/QZ(I)
      IF(ABS(XR).LE.ABS(XLEFT))GO TO 302
      ZRNEW=XRIGHT*(SIGN(XRIGHT,XR)-X(I))/(XR-X(I))
      XR=SIGN(XRIGHT,XR)
      IZ2=NXV(ZRNEW)
  302 IX1=NYV(XL)
      IX2=NYV(XR)
  300 CALL LINEV(IZ1,IX1,IZ2,IX2)
      RETURN
      END
```

```
      SUBROUTINE MTF
C
C     A SUBROUTINE DESIGNED TO COMPUTE THE MODULATION TRANSFER FUNCTION OF AN
C     OPTICAL SYSTEM WITH MODERATE ABERRATIONS.ALSO COMPUTED IS THE PHASE
C     ANGLE PHI ASSOCIATED WITH THE MTF.
C
      COMMON/RAYS/X(201),Y(201),Z(201),QX(201),QY(201),QZ(201),NUM,
     1LABEL(6)
      DIMENSION XP(50),YP(50),ANMTF(50),FREQ(50),PHI(50),TX(201)
      DIMENSION THETA(2)
      DATA CVTR,TWOPI/0.01745329,6.2831853/
C
C     READ IN PLOT CONTROLS. NO. OF FREQUENCIES, STARTING FREQ.,
C     DELTA FREQ., AND TWO AXIS ROTATION ANGLES
C
      READ(5,110) NEMPHS,NCHRS,NFREQ,STFREQ,DFREQ,THETA(1),THETA(2)
 110  FORMAT(3I1J,4F10.4)
      TNUM=NUM
C
C     SET UP PLOTTER
      A1=STFREQ
      A3=A1+(FLOAT(NFREQ)+1.0)*DFREQ
      A2=0.
      A4=1.2
      CALL GRID(A1,A3,A2,A4,DFREQ,.05,NEMPHS,4,NEMPHS,4,NCHRS,3)
      CALL PRINTV(60,LABEL,2.0,1000)
      CALL PRINTV(-9,3HFREQUENCY,500,2)
      CALL APRNT7(0,-14,-10,10HMODULATION,0,600)
C
C
      DO 215  L4=1,2
      FREQ(1)=STFREQ
C
C     ROTATE AXES USING THETA(L4) AND COMPUTE X-PRIME(K) FOR EACH X(K).
C
      DO 115 K=1,NUM
 115  TX(K)=X(K)*COS(THETA(L4)*CVTR)+Y(K)*SIN(THETA(L4)*CVTR)
      DO 130  J3=1,NFREQ
      REG1=0.0
      REG2=0.0
      DO 135  J2=1,NUM
      REG1=REG1+COS(TWOPI*FREQ(J3)*TX(J2))
      REG2=REG2+SIN(TWOPI*FREQ(J3)*TX(J2))
 135   CONTINUE
      AS=REG2/TNUM
      AC=REG1/TNUM
C
C     COMPUTE MTF FROM AS,AC,AND NUM.
C
      ANMTF(J3)=SQRT(AC*AC+AS*AS)
      PHI(J3)=ATAN(AS/AC)
      XP(J3)=FREQ(J3)
      YP(J3)=ANMTF(J3)
      FREQ(J3+1)=FREQ(J3)+DFREQ
 130  CONTINUE
```

```
C
C     PRINT OUT HARD COPY OF RESULTS.
C
      WRITE(6,150) NFREQ,STFREQ,DFREQ,THETA(L4)
 150  FORMAT(1H1,3X,* NFREQ= *,I5,8X,* STARTING FREQ= *,F10.4,8X, *
     1DELTA FREQ= *,F10.4,6X,* TARGET ORIENTATION= *,F10.4,///)
      WRITE(6,160) NEMPHS,NCHRS
 160  FORMAT(1H,3X,* TIC EMPHASIS= *,I5,8X,* TIC CHARACTERS= *,I5,///)
      WRITE(6,155)
 155  FORMAT(10X,* FREQUENCY *,10X,* MTF *,10X,* PHASE ANGLE *,//)
      WRITE(6,158)  (FREQ(J4),ANMTF(J4),PHI(J4),J4=1,NFREQ)
 158  FORMAT(8X,F10.3,8X,F10.4,8X,F10.4)
C
C     PLOT MTF VS. FREQ.
C
      IF(L4.EQ.1) GO TO 102
      IF(L4.EQ.2) GO TO 103
 102  CALL APLOTV(NFREQ,XP(1),YP(1),1,1,1,63,IERR1)
      GO TO 104
 103  CALLAPLOTV(NFREQ,XP(1),YP(1),1,1,1,38,IERR2)
 104  NFR=NFREQ-1
      DO 101  II=1,NFR
      IX1=NXV(XP(II))
      IX2=NXV(XP(II+1))
      IY1=NYV(YP(II))
      IY2=NYV(YP(II+1))
 101  CALL LINEV(IX1,IY1,IX2,IY2)
 215  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SCANS
C     CCCC
```

```
     1*)                                                                820 CTD
      IF(TILT.NE.0.) GO TO 3
      IF((YTR.EQ.0.).AND.(XTR.EQ.0.)) GO TO 10
C
C PERFORM APPROPRIATE COORDINATE TRANSFORMATIONS USING ROTATION AND/OR TRANS-
C LATION PARAMETERS.
C
  3   TILT=TILT*CVTR
      SIT=SIN(TILT)
      CIT=COS(TILT)
      DO 15  J=1,NUM
      T1=X(J)-XTR
      T2=Y(J)-YTR
      X(J)=T1*CIT+T2*SIT
 15   Y(J)=-T1*SIT+T2*CIT
 10   IF(KEY .EQ. ICIR) SS1=SS2=2.0*R                                  CIRTEST
C
C     HORIZONTAL SCAN BEGINS HERE.
C
C COMPUTE STEP SIZE FOR SCANNING.
C
      ANS=NS-1
      SS=(A2-A1)/ANS
C COUNT NUMBER OF RAYS WITHIN THE APERTURE AFTER EACH SCAN STEP.
C
      DO 120  J=1,NS
      RJ=J
      XC(J)=A1+(RJ-1.0)*SS
      NUMC(J)=0
      DO 118  K=1,NUM
      IF(KEY .EQ. ICIR) GO TO 112                                      CIRTEST
      XBL=XC(J)-SS1/2.0
      XBR=XC(J)+SS1/2.0
      YBU=      +SS2/2.0
      YBD=      -SS2/2.0
      IF(X(K).GE.XBL.AND.X(K).LE.XBR.AND.Y(K).GE.YBD.AND.Y(K).LE.YBU)
     1NUMC(J)=NUMC(J)+1
      GO TO 118                                                        CIRTEST
 112  D=SQRT((X (K)-XC(J))**2+(Y (K))**2)                              CIRTEST
      IF(ABS(D).LE.R) NUMC(J)=NUMC(J)+1                                CIRTEST
 118  CONTINUE
 120  CONTINUE
C
C FIND MAXIMUM VALUE OF NO. OF RAYS  AND NORMALIZE EACH NUMBER TO THIS.
C
      MVAL=NUMC(1)
      DO 130  J=2,NS
 130  MVAL= MAX0(MVAL,NUMC(J))
      DO 140  J2=1,NS
      ANUMC(J2)=NUMC(J2)
      AMVAL=MVAL
 140  ANORM(J2)=ANUMC(J2)/AMVAL
      WRITE(6,200)
 200  FORMAT(1H1,3X,* X VALUE *,10X,* NO. OF RAYS *,10X,* INTENSITY *,
     1///)
```

```
      WRITE(6,205) (XC(J),NUMC(J),ANORM(J),J=1,NS)
 205  FORMAT(6X,F10.4,5X,I10,11X,F10.4)
C
C     VERTICAL    SCAN BEGINS HERE.
C
C ROTATE SCANNING RECTANGLE THROUGH 90 DEG IF THIS OPTION WAS CHOSEN.
C
      IF(ORIENT.EQ.REVOLV) GO TO 207
      GO TO 208
 207  SS2P=SS2
      SS2=SS1
      SS1=SS2P
C
C COUNT NUMBER OF RAYS  WITHIN THE SCAN APERTURE AFTER EACH SCAN STEP.
C
 208  DO 220  J=1,NS
      RJ=J
      YC(J)=A1+(RJ-1.0)*SS
      NNUMC(J)=0
      DO 218  K=1,NUM
      IF(KEY .EQ. ICIR) GO TO 212
      XBR=      +SS1/2.0
      XBL=      -SS1/2.0
      YBU=YC(J)+SS2/2.0
      YBD=YC(J)-SS2/2.0
      IF(X(K).GE.XBL.AND.X(K).LE.XBR.AND.Y(K).GE.YBD.AND.Y(K).LE.YBU)
     1NNUMC(J)=NNUMC(J)+1
      GO TO 218                                                         CIRTEST
 212  D=SQRT((Y (K)-YC(J))**2+X (K)**2)                                 CIRTEST
      IF(ABS(D) .LE. R) NNUMC(J)=NNUMC(J)+1                             CIRTEST
 218  CONTINUE
 220  CONTINUE
C
C FIND MAXIMUM VALUE OF NO. OF RAYS  AND NORMALIZE EACH NUMBER TO THIS.
C
      MVAL=NNUMC(1)
      DO 230  J=2,NS
 230  MVAL=MAX0(MVAL,NNUMC(J))
      DO 240  J=1,NS
      ANNUMC(J)=NNUMC(J)
      AMVAL=MVAL
 240  VNORM(J)=ANNUMC(J)/AMVAL
      WRITE(6,300)
 300  FORMAT(1H1,3X,* Y VALUE *,10X,* NO. OF RAYS *,10X,* INTENSITY *,
     1///)
      WRITE(6,305) (YC(L),NNUMC(L),VNORM(L),L=1,NS )
 305  FORMAT(5X,F10.4,5X,I10,11X,F10.4)
C
C     PLOT RESULTS
C
      A3=0.
      A4=1.2
      READ(5,400) DX,N,NCHRS
 400  FORMAT(F10.4,2I10)
      WRITE(6,804) DX,N,NCHRS
```

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```
804  FORMAT(1H1,* TIC SPACING= *,F10.4,8X,* TIC EMPHASIZED= *,I6,8X,
    1* CHARACTERS= *,I6)
     CALL GRID(A1,A2,A3,A4,DX,.05,N,4,N,4,NCHRS,3)
     CALL PRINTV(60,LABEL,270,1000)
     CALL PRINTV(-9,9HSCAN AXIS,500,0)
     CALL APRNTV(0,-14,-9,9HINTENSITY,0,600)
     CALL APLOTV(NS,XC(1),ANORM(1),1,1,1,99,IERR3)
     NSS=NS-1
     DO 410 JJ=1,NSS
     IX1=NXV(XC(JJ))
     IX2=NXV(XC(JJ+1))
     IY1=NYV(ANORM(JJ))
     IY2=NYV(ANORM(JJ+1))
410  CALL LINEV(IX1,IY1,IX2,IY2)
     CALL APLOTV(NS ,YC(1),VNORM(1),1,1,1,38,IERR4)
     NSPP=NS -1
     DO 420 KK=1,NSPP
     IX1=NXV(YC(KK))
     IX2=NXV(YC(KK+1))
     IY1=NYV(VNORM(KK))
     IY2=NYV(VNORM(KK+1))
420  CALL LINEV(IX1,IY1,IX2,IY2)
     RETURN
     END


     SUBROUTINE GRID(XLEFT,XRIGHT,YDOWN,YUP,DX,DY,N,M,I,J,NX,NY)
C
C    DRAW AND LABEL GRID
     CALL FRAMEV(0)
     CALL XSCALV(XLEFT,XRIGHT,88,43)
     CALL YSCALV(YDOWN,YUP,88,43)
     CALL LINEV(88,88,88,980)
     CALL LINEV(88,980,980,980)
     CALL LINEV(980,980,980,88)
     CALL LINEV(88,88,980,88)
     CALL LINRV(1,76,88,98,XLEFT,XRIGHT,DX,N,I,NX,8)
     CALL LINRV(2,24,88,98,YDOWN,YUP,DY,M,J,NY,10)
     CALL LINRV(1,76,970,980,XLEFT,XRIGHT,DX,N,0,NX,8)
     CALL LINRV(2,24,970,980,YDOWN,YUP,DY,M,0,NY,10)
     RETURN
     END


     SUBROUTINE INITIL
C
C    INITIALIZE PLOTS
     CALL CAMRAV(9,9)
     CALL FRAMEV(0)
     CALL XAXISV(0,0)
     CALL XAXISV(0,1023)
     CALL YAXISV(0,0)
     CALL YAXISV(1023,0)
     CALL PRINTV(-21,21HPLOTS FOR HYMAN CURRY,360,490)
     RETURN
     END
```

Appendix B

INPUT FOR IMAGE ANALYSIS PROGRAM

MAIN PROGRAM

Card Group	Format	Parameters
1 (1 card)	(6A10)	LABEL LABEL = Title of Run
2 (1 card)	(F10.0)	DELD DELD = Signed axial separation between final optical surface vertex and the image plane
3 (1 card) Punched by FOLDP	(I10)	N N = Total number of rays on the final optical surface
4 (N cards) Punched by FOLDP	(6E13.7)	X, Y, Z, QX, QY, QZ Coordinates and direction cosines of each ray, one ray per card

SUBROUTINE RAPLOT

5 (1 card)	(2F10.0, 2I10)	SCALE, DELTXY, NEMPHS, NCHRS SCALE = Plot scale (halfwidth) DELTXY = Plot tic increment NEMPHS = Tic emphasis NCHRS = Tic label characters (including decimal)

SUBROUTINE MTF

6 (1 card)	(3I10, 4F10.4)	NEMPHS, NCHRS, NFREQ, STFREQ, DFREQ, THETA(1), THETA(2) NEMPHS = Tics to emphasize NCHRS = Tic label characters NFREQ = Number of discrete frequencies STFREQ = Starting frequency

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Card Group		Format	Parameters
			DFREQ = Frequency increment THETA(1) = First scan angle (degrees) THETA(2) = Second scan angle (degrees)
7	(1 card)	(I10, 6F10.0, A6)	NS, SS1, SS2, R, YTR, XTR, TILT, KEY NS = Number of scan steps or positions SS1 = X aperture dimension SS2 = Y aperture dimension R = Radius of aperture YTR = Y translate coordinate XTR = X translate coordinate TILT = Axis rotation (degrees) KEY = "CIRCLE" if circular aperture KEY = Blank if rectangular aperture
8	(1 card)	(2F10.0)	A1, A2 A1 = X starting point (smallest) A2 = X ending point (largest)
9	(1 card)	(A6)	ORIENT ORIENT = "ROTATE" to rotate Y aperture ORIENT = Blank for no rotation of Y aperture
10	(1 card)	(F10.0, 2I10)	DX, N, NCHRS DX = Tic increment N = Nth tic to be emphasized and labeled NCHRS = Tic label characters