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B. Zurro
P. W. King
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OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

ORNL/TM-7168
Dist. Category UC-20 f

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

A RAY TRACING PACKAGE THROUGH A LENS SYSTEM AND A SPECTROMETER

B. Zurro,* P. W. King, and E. A. Lazarus

Date Published - March 1980

*Vistor from Junta de Energia Nuclear, Madrid, Spain.

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

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ABSTRACT

To study the light collection optics of the ISX-B two-dimensional (2-D) Thomson scattering system, we have implemented in the Oak Ridge National Laboratory (ORNL) Fusion Energy Division (FED) PDP-10 two computer programs, LENS and SPECT, that trace rays through a lens system and a spectrometer, respectively. The lens package follows the path of any kind of ray (meridional or skew) through a centered optical system formed by an arbitrary number of spherical surfaces. The spectrometer package performs geometrical ray tracing through a Czerney-Turner spectrometer and can be easily modified for studying any other configuration. Contained herein is a description of the procedures followed and a listing of the computer programs.

1. INTRODUCTION

For most of the optical problems that one has to face in a plasma laboratory, the ray tracing packages available in computer libraries are either too sophisticated for practical applications or not well documented. Thus, difficulties are encountered when one tries to modify the packages to satisfy the requirements of a particular application.

In this report we describe in some detail the ray tracing procedures that we have implemented in the Oak Ridge National Laboratory (ORNL) Fusion Energy Division (FED) PDP-10 and that apply to a collection lens system and a Czerney-Turner spectrometer. These procedures have been implemented to study several aspects of the collection and focusing properties of the ISX-B two-dimensional (2-D) Thomson scattering system, but they are general enough to be used for any optical application involving lenses and spectrometers.

The lens package follows the path of any kind of ray (meridional or skew) through a centered optical system formed by an arbitrary number of spherical surfaces. The spectrometer package performs a geometric ray tracing through a Czerney-Turner spectrometer and can be easily modified for studying any other configuration. These packages can be useful tools for (1) optimization and/or modification of a commercial system and (2) design of new and original units. In the Appendix, we include a listing of the codes with comments.

2. ALGEBRAIC RAY TRACING THROUGH A CENTERED OPTICAL SYSTEM

The multistation Thomson scattering system for the ISX-B tokamak incorporates an f/2 wide-angle lens.[1] To study the optical image that this lens forms of a laser beam in a plasma, we have implemented a ray tracing program in the PDP-10. This allows us to simulate the actual conditions of the experiment and to view the optical image on the Tektronix screen.

The present ray tracing code permits us to follow any kind of ray (meridional or skew) through a centered optical system formed by an arbitrary number of spherical surfaces. For each element we define a three-dimensional (3-D) cartesian system (X, Y, Z), with Z along the optical axis. The origin of the system is the intersection point of each surface with this axis.

The elemental step of the ray tracing is to follow a ray from one optical surface to the next one. Let us define the ray going from surface s-1 to surface s by its direction cosines (ℓ_{s-1}, m_{s-1}, n_{s-1}) and its point of intersection with the surface s-1 (X_{s-1}, Y_{s-1}, Z_{s-1}); all these data refer to the coordinate system of the surface s-1. We will designate by μ_{s-1} and μ_s, respectively, the refraction indices of the media before and after the optical surface s, by ρ the inverse radius of the surface, and by t the separation between adjacent surfaces.

With these assumptions it can be demonstrated[2] that the direction cosines of the ray upon leaving the surface s (ℓ_s, m_s, n_s) and its intersection with s (X_s, Y_s, Z_s) are given by the expressions

$$\ell_s = \ell_{s-1} + P_s \rho_s X_s \ ,$$

$$m_s = m_{s-1} + P_s \rho_s Y_s \ , \tag{1}$$

$$n_s = n_{s-1} + P_s (\rho_s Z_s - \ell) \ ,$$

and

$$X_s = X_{s-1} + \ell_{s-1} \tau_{s-1} ,$$

$$Y_s = Y_{s-1} + m_{s-1} \tau_{s-1} , \qquad (2)$$

$$Z_s = Z'_{s-1} + n_{s-1} \tau_{s-1} ,$$

where

$$Z'_{s-1} = Z_{s-1} - t_{s-1} ,$$

$$P_s = \mu_{s-1} \cos i_s - \mu_s \cos r_s , \qquad (3)$$

$$\tau_{s-1} = A/(B - \mu_{s-1} \cos i_s) ,$$

and

$$A = 2 Z'_{s-1} - \rho_s (X^2_{s-1} + Y^2_{s-1} + Z'^2_{s-1}) , \qquad (4)$$

$$B = \ell_{s-1} \rho_s X_{s-1} + m_{s-1} \rho_s Y_{s-1} + n_{s-1} (\rho_s Z'_{s-1} - \ell) . \qquad (5)$$

The trigonometric functions of the angles i_s and r_s (the incidence and refraction angles at surface s) in the former expressions can be deduced by the formulas

$$\mu^2_{s-1} \sin^2 i_s = (\ell_{s-1} \rho_s Y_{s-1} - m_{s-1} \rho_s X_{s-1})^2$$
$$+ [m_{s-1} \rho_s (Z'_{s-1} - \ell) - n_{s-1} \rho_s Y_{s-1}]^2 , \qquad (6)$$

$$\mu_{s-1} \cos i_s = (\mu_{s-1}^2 - \mu_{s-1}^2 \sin^2 i_s)^{1/2} ,$$

and

$$\mu_s \cos r_s = (\mu_s^2 - \mu_{s-1}^2 \sin^2 i_s)^{1/2} .$$

The basic ray tracing step contained in the former expressions has been implemented in subroutine RATRA (see Appendix). To extend this elemental process to a whole optical system, one must know (1) the inverse radius of the optical surfaces, (2) the refractive indices of the media, and (3) the relative position of the various optical elements (i.e., the separation between optical surfaces measured along the optical axis).

Once the particular configuration of the optical system is fixed, we must define the initial rays coming from the object. One way of doing this is to give the coordinates of an object point and the direction cosines of the ray. To avoid the drawbacks of following rays that do not go through the system, we will define the initial rays by choosing two points, one in the object and another in the input pupil of the system. By mapping those two areas we can study the path of any kind of ray going through the system.

3. GEOMETRIC RAY TRACING THROUGH A CZERNEY-TURNER SPECTROMETER

To study the possible drawbacks of using a small monochromator as the basic unit for the ISX-B multipoint Thomson scattering system, which will use 15 of them, we have implemented in the FED PDP-10 a computer package that performs geometric ray tracing through a Czerney-Turner monochromator. The basic vector equations[3] we have used permit a formulation of the problem independent of the coordinate system, and they can be applied to any other type of spectrometer, even to those that incorporate the very popular concave grating.

The light input cone is defined by fixing two points, one on the input slit and another on the physical mask placed on the first mirror. With a mapping of those areas we can follow the path of a discrete number of rays entering the system.

The intersection point P_M of a ray (with direction $\bar{\ell}_k$) with the first mirror of radius R is given by

$$\bar{P}_M = \bar{P}_o + \left[-\bar{\ell}_k \cdot \bar{P}_o + \sqrt{(\bar{\ell}_k \cdot \bar{P}_o)^2 - P_o^2 + R^2}\right]\bar{\ell}_k \ , \tag{7}$$

where $\bar{P}_o$ is the vector position of the initial point of the ray on the input slit. The reflection of the ray at the mirror is governed by the vector equation

$$\bar{\ell}'_k = \bar{\ell}_k - 2\ (\bar{\ell}_k \cdot \bar{\ell}_n)\bar{\ell}_n \ , \tag{8}$$

where ℓ_k and $\bar{\ell}'_k$ are the incident and reflected ray unit vectors, respectively, and $\bar{\ell}_n$ is the surface normal in either direction.

After the ray is reflected at the first mirror, we determine the intersection point P_G of the ray with the diffraction grating plane given by

$$\bar{P}_G = \bar{P}_M + \frac{(\bar{C} - \bar{P}_M) \cdot \bar{\ell}_n}{\bar{\ell}'_k \cdot \bar{\ell}_n}\,\bar{\ell}'_k \ , \tag{9}$$

where $\overline{C}$ is the vector position of an arbitrary point in the grating (e.g., the center) and $\overline{\ell}_n$ is the unit vector normal to the grating in either direction. At this stage we check whether the ray hits the grating or not. If it is not lost, the ray will be diffracted by the grating in the direction $\overline{\ell}'_k$ given by

$$\overline{\ell}'_k = (\overline{\ell} - a^2 - b^2)\overline{\ell}_1 + a\overline{\ell}_2 + b\overline{\ell}_3 \quad (10)$$

where

$$a = \overline{\ell}'_k \cdot \overline{\ell}_2 - \frac{m\lambda}{nd} ,$$
$$b = \overline{\ell}'_k \cdot \overline{\ell}_3 , \quad (11)$$

and

$$m = 0, \quad \pm 1, \pm 2, \dots ,$$

where $\overline{\ell}_3$ is along the direction of the ruling, m is the diffraction order, λ is the vacuum wavelength, d is the spacing of the rulings, and $\overline{\ell}_2$ (= $\overline{\ell}_3 \times \overline{\ell}_1$) is parallel to the grating surface at right angles to the rulings. The vector $\overline{\ell}_1$ must point out of the grating surface.

We deal with the second mirror in a similar way as the first one. We count the rays that do not hit the mirror, and when this happens we start with a new ray. Finally, to determine the intersection of the ray with the image plane we apply Eq. (9). These intersection points form the image of the input slit and are plotted on the Tektronix screen.

4. PROGRAM DESCRIPTIONS

4.1 SUBPROGRAMS

Both packages, LENS and SPECT, are written in single precision FORTRAN IV. They run on the PDP-10 at ORNL's User Service Center. The graphics are written in the Display Integrated Software System and Plotting Language (DISSPLA). The subprograms are listed below with brief summaries of their functions.

LENS — Sets the data of the optical system, maps the object and input pupil, drives subroutine RATRA, and plots the image on the Tektronix screen.
RATRA — Follows the optical ray path from one optical surface to the next one.
SPECT — Traces rays through a Czerney-Turner spectrometer and plots the image on the Tektronix screen.

To execute both programs one must simply type

EX LENS, RATRA, @PUB:DISTEK (for the lens package)

and

EX SPECT, @PUB:DISTEK (for the spectrometer package) .

4.2 INPUT

The main data for running LENS (i.e., the optical surface inverse radius, separation between surfaces, and refraction indices) are given to the program by means of DATA statements. The data related to the object (e.g., width and height of the laser beams) and to the image (e.g., image plane position) are given through the Teletype.

SPECT uses a namelist input data file named TDTS, which is stored in FOR13.DAT. This set of variables is described in Table 1.

Table 1. Spectrometer ray tracing namelist input

FORTRAN name	Definition	Units
XSI, ZSI	Input slit coordinates	mm
N1, N2	N1 × N2 = number of points on input slit (for mapping)	
WSI, HIS	Width and height of the input slit	mm
GSIZE	Grating size	mm
D	Distance between grooves	nm
ALFA	Grating angle	degrees
R1, R2	Curvature radius of objective, camera mirrors	mm
XSV1, ZMV1	Position coordinates of the objective mirror	mm
XMV2, ZMV2	Position coordinates of the camera mirror	mm
SMASK	Size of the mask on both mirrors	mm
N3	N3 × N3 = number of grid points on the mask	
ALAM	Initial wavelength	nm
DLA	Wavelength step	nm
NA	Number of discrete wavelengths	

4.3 OUTPUT

Graphics showing the image points on the Tektronix screen are the main output of both programs. The coordinates of the image points may also be typed by the Teletype.

4.4 APPLICATIONS

LENS and SPECT have been applied to model the wide-angle lens and the monochromator HR-320 (Instruments SA, Inc.) that will be installed in the new ISX-B Thomson scattering system; both components are sketched in Fig. 1.

Figure 2 shows the image structure produced by the f/2 lens for the scattered light. The image is seen as it will be viewed by the fiber optical bundle that will relay it from the focal plane of the lens to the input slits of the spectrometer, for three different positions of the bundle. The figure shows how sensitive the quality of the image collected by the fiber guides is to the location of the fiber guides.

We show in Fig. 3 the image of the monochromator HR-320 input slit as obtained by SPECT for four different wavelengths. We have followed the same number of rays for all the wavelengths, but the number reaching the image plane is higher for the central part of the focal field due to the vignetting of the system. We plot in Fig. 4 the vignetting losses (%) vs wavelength for this monochromator when it is used as a spectrograph in a Thomson scattering system.

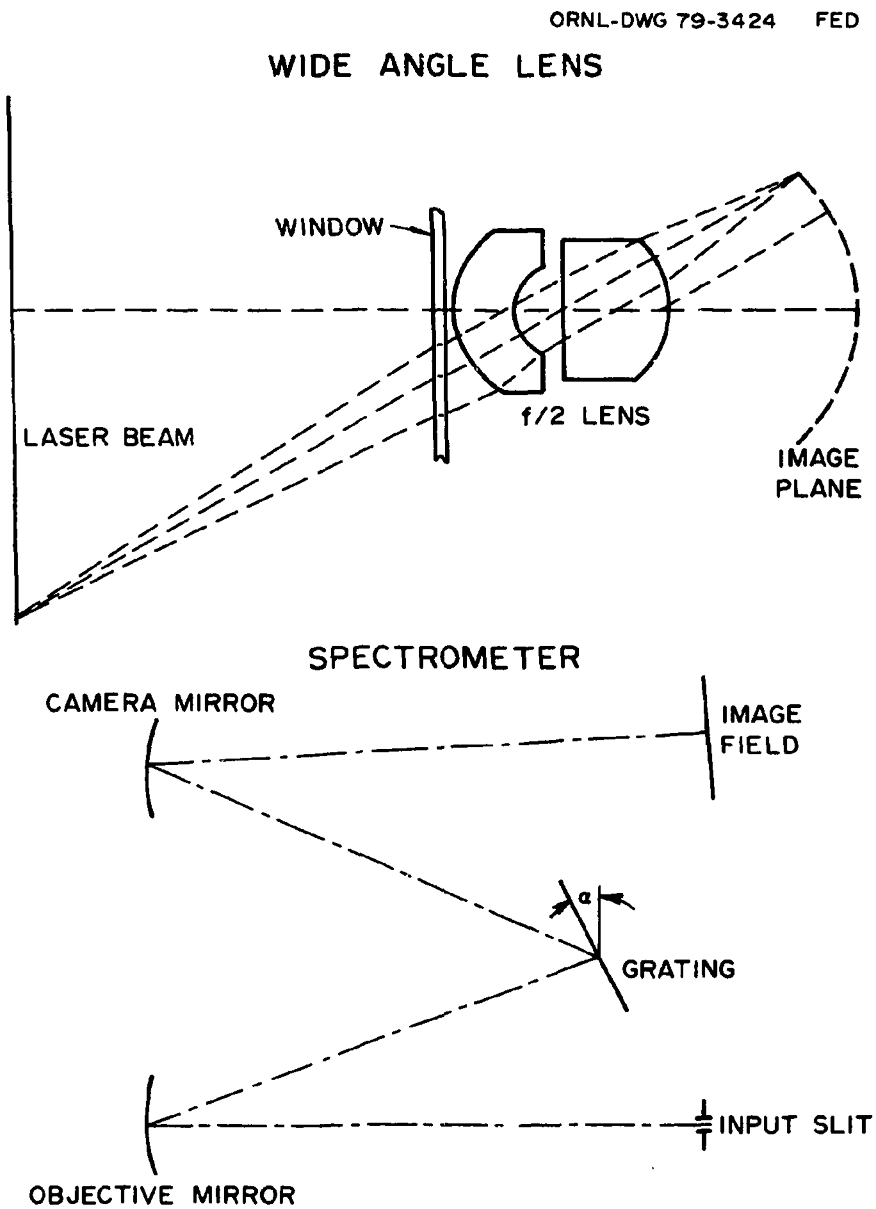

Fig. 1. Sketch of the optical systems modeled by LENS and SPECT.

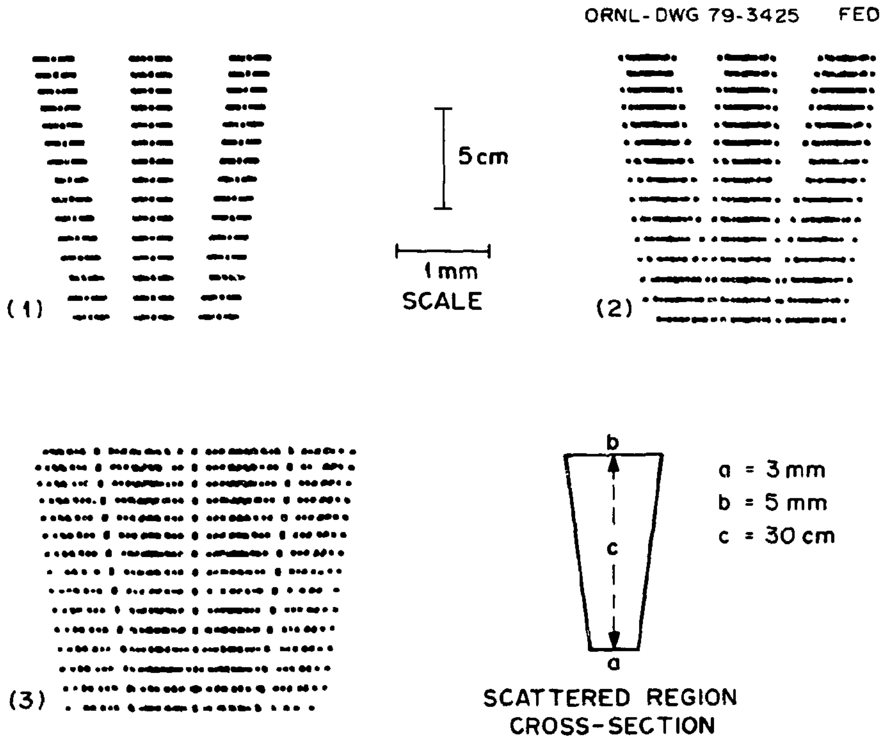

Fig. 2. Optical images of the scattering region as obtained by ray tracing through the f/2 lens using a discrete number of points in the object, for three positions of the focal plane: (1) best focus, (2) best focus + 0.5 cm, and (3) best focus - 0.5 cm.

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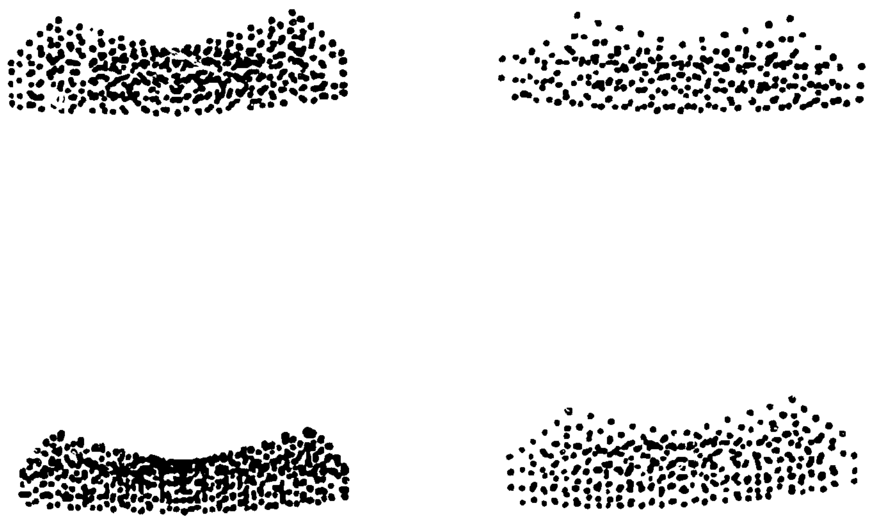

Fig. 3. Spectrometer ray tracing results showing the image of an infinitesimal narrow input slit for four wavelengths (700, 725, 750, and 775 nm); the 1200 grooves/mm grating was kept fixed.

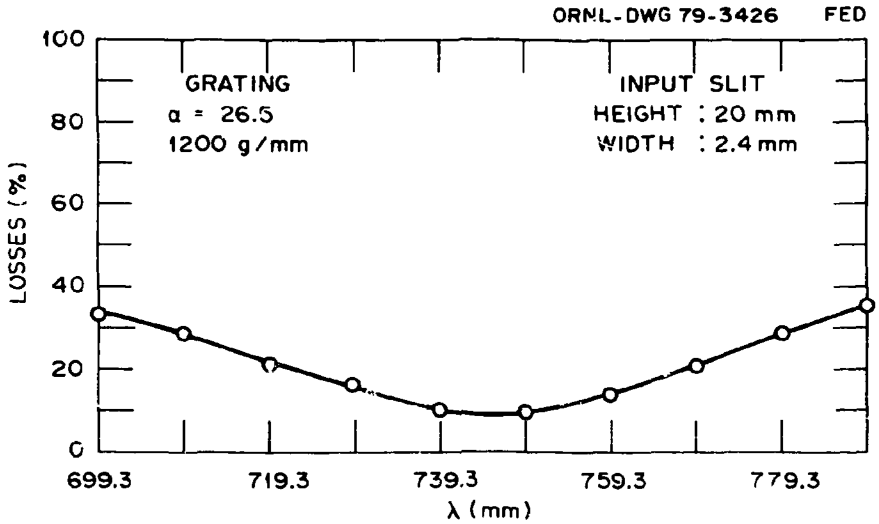

Fig. 4. Vignetting losses (%) of the HR-320 for a particular configuration.

REFERENCES

1. N. Bretz, D. Dimock, V. Foote, D. Johnson, D. Lory, and E. Tolnas, Princeton Plasma Physics Laboratory Report PPPL-1356, Princeton, New Jersey (1977).
2. A. Cox, *A System of Optical Design*, Focal Press, New York, 1964.
3. J. W. Horwitz, Opt. Acta 21, 169 (1974).

APPENDIX

LENS

```
C        A RAY TRACING PROGRAM TH... H THE TDTS WIDE ANGLE LENS
C
         DIMENSION COSDI(50),XR(5,10),YR(5,10),ZR(5,10)
         DIMENSION XPO(10000),YPO(10000),ROG(10),ENDR(10),TE(10)
C
C        SEPARATION BETWEEN OPTICAL SURFACES - OBJECT AND IMAGE PLANE
C        ARE CONSIDERED AS OPTICAL SURFACES-
C
         DATA(TE(I),I=1,7)/63.2,3.174,2.626,8.3614,6.6936,14.2455,
     224.17/
C
C        INVERSE OF SURFACE RADIUS
C
         DATA(ROG(I),I=1,7)/0.,0.,0.066422,0.149395,0.,-0.070197,
     2-0.03789/
C
C        REFRACTION INDEX BETWEEN SURFACES
C
         DATA(ENDR(I),I=1,8)/1.,1.455446,1.,1.791165,1.512893,
     21.512893,1.,1./
         KP=0
         TYPE 93
93       FORMAT(2X,'FOCUS (24.17)')
         ACCEPT *,TE(7)
         TYPE 9
9        FORMAT(2X,' BEAM DIMENSIONS(WIHDS BX1,BX2) HEIGHT BY')
         ACCEPT *,BX1,BX2,BY
C
C        LASER BEAM MAPPING
C
         DO 104 I2=1,15
         YM0=FLOAT(I2-1)*BY/14.
         DO 103 I1=1,3
         BX=BX1+(BX2-BX1)*YM0/BY
         XM0=BX/2.-FLOAT(I1-1)*BX/2.
         K=1
C
C        INPUT PUPIL MAPPING
C
         DO 200 I=1,5
         DO 300 J=1,8
         RI=4.-FLOAT(I-1)*1.
         TETA=FLOAT(J-1)*45.
         XP=RI*COSD(TETA)
         YP=RI*SIND(TETA)
         OP=SQRT((XP-XM0)**2+(YP-YM0)**2+84.055**2)
C
C        INPUT RAY DIRECTION COSINES.THEY ARE DEFINED FIXING A POINT IN
C        THE OBJECT (XM0,YM0) AND A POINT ON THE INPUT PUPIL (XP,YP)
C
         EL=(XP-XM0)/OP
         EM=(YP-YM0)/OP
         EN=84.055/OP
         XM1=XM0
         YM1=YM0
         ZM1=0.
         DO 100 L=1,7
```

```
      RO=ROG(L)
      T=TE(L)
      ENM1=ENDR(L)
      EN1=ENDR(L+1)
C
C     RAY TRACING THROUGH AN OPTICAL SURFACE
C
C     (XM1,YM1,ZM1) COORDINATES OF THE RAY INTERSECTION WITH THE
C     PREVIOUS OPTICAL SURFACE
C     ENM1 - REFRACTION INDEX OF THE OBJECT SPACE
C     EN1  -     ''         ''          IMAGE SPACE
C     EL,EM,EN DIRECTION COSINES OF THE RAY
C     (X,Y,Z) COORDINATES OF THE RAY INTERSECTION WITH THE OPTICAL
C     SURFACE
      CALL RATR(XM1,YM1,ZM1,EL,EM,EN,RO,T,ENM1,EN1,X,Y,Z)
      XM1=X
      YM1=Y
      ZM1=Z
100   CONTINUE
      XR(I,J)=X
      YR(I,J)=Y
      ZR(I,J)=Z
      XPO(KP)=X
      YPO(KP)=Y
      KP=KP+1
      COSDI(K)=EN
      K=K+1
300   CONTINUE
200   CONTINUE
      GOTO 700
      COSZ=0.
      DO 600 K=1,33
      COSDI(K)=57.29578*ACOS(COSDI(K))
600   COSZ=COSZ+COSDI(K)
      COSZ=COSZ/33.
      TYPE 550,COSZ
550   FORMAT(E12.5)
      TYPE 570,(COSDI(I),I=1,33)
570   FORMAT(5E12.5)
500   CONTINUE
700   CONTINUE
      GOTO 903
      TYPE 749
749   FORMAT(//9X,'X',14X,'Y',13X,'Z')
      DO 750 I=1,5
      TYPE 800,(XR(I,J),YR(I,J),ZR(I,J),J=1,8)
800   FORMAT(3X,E12.4,3X,E12.4,3X,E12.4)
750   CONTINUE
903   CONTINUE
103   CONTINUE
104   CONTINUE
      PAUSE
1500  TYPE 1550
1550  FORMAT(2X,' X1,X2')
      ACCEPT *,X1,X2
      CALL TKTRN(1200,0)
      CALL BGNPL(-1)
      CALL TITLE('IMAGES$',-100,'HORIZONTAL',100,'VERTICAL',100,
     210.,6.)
      ST=(X2-X1)/5.
```

```
CALL GRAF(X1,ST,X2,-5.,5.,20.)
CALL MARKER(2)
CALL SCLPIC(0.1)
CALL CURVE(XPO,YPO,KP,-1)
CALL ENDPL(0)
GOTO 1500
STOP
END
```

RATRA

```
SUBROUTINE RATR(XM1,YM1,ZM1,EL,EM,EN,RO,T,ENM1,EN1,X,Y,Z)
ZP=ZM1-T
A=(EL*RO*YM1-EM*RO*XM1)**2
B=(EM*(RO*ZP-1.)-EN*RO*YM1)**2
C=(EN*RO*XM1-EL*(RO*ZP-1.))**2
SEN2=(A+B+C)/ENM1**2
COSIS=(ABS(ENM1**2-SEN2*ENM1**2))**0.5/ENM1
COSRS=(ABS(EN1**2-SEN2*ENM1**2))**0.5/EN1
AB=2.*ZP-RO*(XM1**2+YM1**2+ZP**2)
AC=EL*RO*XM1+EM*RO*YM1+EN*(RO*ZP-1.)
TAU=AB/(AC-ENM1*COSIS)
P=ENM1*COSIS-EN1*COSRS
X=XM1+EL*TAU
Y=YM1+EM*TAU
Z=ZP+EN*TAU
ELS=EL+P*RO*X
EMS=EM+P*RO*Y
ENS=EN+P*(RO*Z-1.)
EL=ELS
EM=EMS
EN=ENS
RETURN
END
```

SPECT

```
C       RAY TRACING PROGRAM THROUGH A CZERNY-TURNER SPECTROMETER
C
C       COORDINATE SYSTEM:
C
C       X-AXIS : ALONG THE LONGITUDINAL AXIS OF THE SPECTROMETER
C                AND PASSING THROUGH THE GRATING CENTER.
C
C       Z-AXIS : PASSING THROUGH THE CURVATURE CENTER OF THE OBJECTIVE
C                MIRROR.
C
C       NAMELIST FILE : FOR13.DAT
C
C       DATA:
C
C       INPUT SLIT.
C
C       XSI,ZSI - X,Z COORDINATES OF AN INPUT SLIT POINT
C       WSI,HIS - WIDTH AND HEIGHT OF THE INPUT SLIT
C       N1,N2   - N1*N2=NUMBER OF POINTS ON THE INPUT SLIT
C
C       GRATING.
C
C       GSIZE   - SIZE OF THE GRATING
C       D       - DISTANCE BETWEEN GROOVES(NM)
C       ALFA    - ANGLE BETWEEN THE GRATING PLANE AND THE Z AXIS(DEGREES)
C
C       MIRRORS.
C
C       R1,R2       - CURVATURE RADIUS OF OBJECTIVE AND CAMERA MIRRORS
C       XMV1,ZMV1   - POSITION COORDINATES OF THE OBJECTIVE MIRROR
C       XMV2,ZMV2   - POSITION COORDINATES OF THE CAMERA MIRROR
C       SMASK       - SIZE OF THE MASK ON BOTH MIRRORS
C       N3          - N3*N3 = NUMBER OF GRID POINTS ON THE MASK
C
C                           WAVELENGTHS.
C
C       N4    - NUMBER OF DISCRETE WAVEL.
C       ALAM  - INITIAL WAVEL.
C       DLA   - WAVEL. STEP (NM)


        DIMENSION XES(7,17,8,8,3),YES(7,17,8,8,3),ZES(7,17,8,8,3)
        DIMENSION Y(25000),Z(25000)
        NAMELIST/TDTS/XSI,ZSI,WIS,HIS,N1,N2,GSIZE,D,ALFA,XGC,
     2N4,ALAM,DLA,R1,R2,XMV1,ZMV1,XMV2,ZMV2,SMASK,N3
     3,XOS,ZOS
        READ(13,TDTS)
        XCM1=XMV1-COSD(5.739)*R1
        ZCM1=-(ABS(ZMV1)-SIND(5.739)*R1)
        XM2C=XMV2-COSD(5.739)*R2
        ZM2C=ZMV2-SIND(5.739)*R2
        IRC=0
        IM2=0
        M=1
        AZ=ZSI-WIS/2.
        DZ=WIS/FLOAT(N1-1)
        DY=HIS/FLOAT(N2-1)
```

```
      DSM=SMASK/FLOAT(N3-1)
      DO 100 I=1,N1
      ZSI=AZ+DZ*FLOAT(I-1)
      DO 200 J=1,N2
      YSI=-HIS/2.+DY*FLOAT(J-1)
      DO 300 K1=1,N3
      XM0=XMV1
      YM0=-SMASK/2.+DSM*FLOAT(K1-1)
      DO 400 K2=1,N3
      ZM0=-(ABS(ZMV1)+SMASK/2.)+DSM*FLOAT(K2-1)
      DO 500 K3=1,N4
      ALAMB=ALAM+DLA*FLOAT(K3-1)
C
C     CALCULATES DIRECTION COSINES FOR INPUT LIGHT CONE
C
      OP=SQRT((XM0-XSI)**2+(YM0-YSI)**2+(ZM0-ZSI)**2)
      EL=(XM0-XSI)/OP
      EM=(YM0-YSI)/OP
      EN=(ZM0-ZSI)/OP
C
C     INTERSECTION FIRST MIRROR AND DIRECTION COSINES
C     AFTER REFLECTION
C
      XSI=XSI-XCM1
      ZSI=ZSI-ZCM1
      A=EL*XSI+EM*YSI+EN*ZSI
      B=XSI**2+YSI**2+ZSI**2
      XM1=XSI+(SQRT(A**2-B+R1**2)-A)*EL
      ZM1=ZSI+(SQRT(A**2-B+R1**2)-A)*EN
      YM1=YSI+(SQRT(A**2-B+R1**2)-A)*EM
      XM1=XM1+XCM1
      ZM1=ZM1+ZCM1
      ELN=(XM1-XCM1)/R1
      EMN=YM1/R1
      ENN=(ZM1-ZCM1)/R1
      A=EL*ELN+EM*EMN+EN*ENN
      ELS=EL-2.*A*ELN
      EMS=EM-2.*A*EMN
      ENS=EN-2.*A*ENN
      XSI=XSI+XCM1
      ZSI=ZSI+ZCM1
C
C     GRATING INTERSECTION AND DIFRACTED DIRECTION
C
      A=(XGC-XM1)*COSD(ALFA)-ZM1*SIND(ALFA)
      B=ELS*COSD(ALFA)+ENS*SIND(ALFA)
      XG=XM1+A*ELS/B
      YG=YM1+A*EMS/B
      ZG=ZM1+A*ENS/B
      ALI=GSIZE*COSD(ALFA)/2.
      ALI=ABS(ALI)
      AZG=ABS(ZG)
      AYG=ABS(YG)
      ZZG=ALI-AZG
      YYG=GSIZE/2.-AYG
      IF(YYG)61,61,62
      IF(ZZG) 61,61,62
61    IRC=IRC+1
      GOTO 63
62    A=ELS*SIND(ALFA)-ENS*COSD(ALFA)-ALAMB/D
```

```
      B=EMS
      AB=SQRT(1.-A**2-B**2)
      ELS=AB*COSD(ALFA)+A*SIND(ALFA)
      EMS=B
      ENS=AB*SIND(ALFA)-A*COSD(ALFA)
      XG=XG-XM2C
      ZG=ZG-ZM2C
C
C     INTERSECTION SECOND MIRROR AND REFLECTION
C
      A=ELS*XG+EMS*YG+ENS*ZG
      B=XG**2+YG**2+ZG**2
      AB=SQRT(A**2-B+R2**2)-A
      XM2=XG+AB*ELS
      YM2=YG+AB*EMS
      ZM2=ZG+AB*ENS
      XM2=XM2+XM2C
      ZM2=ZM2+ZM2C
      AZ2=ABS(ZMV2-ZM2)
      AY2=ABS(YM2)
      IF(SMASK/2.-AZ2)64,65,65
      IF(SMASK/2.-AY2)64,65,65
64    IM2=IM2+1
      GOTO 63
65    ELN=(XM2-XM2C)/R2
      EMN=YM2/R2
      ENN=(ZM2-ZM2C)/R2
      A=ELN*ELS+EMN*EMS+ENN*ENS
      ELS=ELS-2.*A*ELN
      EMS=EMS-2.*A*EMN
      ENS=ENS-2.*A*ENN
C
C     CALCULATES  IMAGE POINTS
C
      A=((XOS-XM2)*COSD(2.417)-(ZOS-ZM2)*SIND(2.417))/
     2(ELS*0.99911-ENS*0.042172)
      XES(I,J,K1,K2,K3)=XM2+A*ELS
      YES(I,J,K1,K2,K3)=YM2+A*EMS
      ZES(I,J,K1,K2,K3)=ZM2+A*ENS
      Y(M)=YES(I,J,K1,K2,K3)
      Z(M)=ZES(I,J,K1,K2,K3)-ABS(ZOS)
      M=M+1
63    CONTINUE
500   CONTINUE
400   CONTINUE
300   CONTINUE
200   CONTINUE
100   CONTINUE
      TYPE 149,M,IRC,IM2
149   FORMAT(5X,3I10)
290   TYPE 150
150   FORMAT(2X,'I1,I2,I3,I4,I5,IP')
      ACCEPT 160,I1,I2,I3,I4,I5,IP
160   FORMAT(I1,I2,4I1)
      ZQ=ZES(I1,I2,I3,I4,I5)-ABS(ZOS)
      TYPE 260,YES(I1,I2,I3,I4,I5),ZQ
260   FORMAT(5X,E14.4,5X,E14.4)
      IF(IP.EQ.1) GOTO 290
1550  TYPE 1500
1500  FORMAT(2X,' Z1,Z2')
```

```
      ACCEPT *,Z1,Z2
      PAUSE
C     TEKTRONIX SCREEN PLOTTING
      CALL TKTRN(1200,0)
      CALL BGNPL(-1)
      CALL TITLE('IMAGES$',-100,'HORIZONTAL',100,'VERTICAL',
     2100,10.,6.)
      ST=(Z2-Z1)/5.
      CALL GRAF(Z1,ST,Z2,-16.,4.,16.)
      CALL MARKER(2)
      CALL SCLPIC(0.1)
      CALL CURVE(Z,Y,M,-1)
      CALL ENDPL(0)
      GOTO 1550
      STOP
      END
```