

**RAY:
A MENU DRIVEN RAY TRACE PROGRAM**

Instruction Manual (MSDOS version 6.60)

Terry Herter and James R. Houck

Manual Version 1.0
Revised: 25-Oct-2001

TABLE OF CONTENTS

1. OVERVIEW	1
1.1. General Description	1
1.2. Program History	1
2. PROGRAM STRUCTURE.....	2
2.1. Overview	2
2.2. Main Menu	2
2.3. Prescription Menu	4
2.4. Special Surfaces.....	6
2.5. Tracing Rays	8
2.6. Parameter Optimization Menu.....	10
2.7. Parameter Variation Menu	14
3. RAYTRACE OUTPUT FORMATS:	15
3.1. A Note on Dimensions.....	16
3.2. Hard Copies.....	17
4. REVISION HISTORY	17
5. APPENDIX I: CASSEGRAIN EXAMPLE.....	18
6. APPENDIX B: A RAYTRACE TUTORIAL.....	22

LIST OF TABLES

Table 1 : Main Menu Command Descriptions	3
Table 2 : Prescription Menu Command Descriptions.....	4
Table 3 : Special Surface Descriptions	6
Table 4 : Trace Menu Command Descriptions.....	8
Table 5 : Parameter Optimization Menu Descriptions.....	11

LIST OF FIGURES

Figure 1 : Main Menu	2
Figure 2 : Prescription Menu	4
Figure 3 : Trace Menu.....	8
Figure 4 : Parameter Optimization Menu	11
Figure 5 : Vary Parameter Setup Menu	14

1. OVERVIEW

1.1. General Description

RAY is a general ray-trace program that will trace rays through a specified optical system and generate spot diagrams as well as RMS statistics and focal shift information. Conic and aconic surfaces of revolution are allowed as are cylindrical conic sections, toroidal surfaces, diffraction gratings, prisms, aperture stops and obscurations. All of these surfaces can be tipped and/or offset from the optical axis. Real co-ordinate transformations (both displacements and rotations) are allowed to ease the specification of "bent" systems such as spectrometers. A total of 30 surfaces are permitted including all optical elements and dummy surfaces inserted for obscurations and coordinate transformations.

Although RAY does not perform optimizations in the manner of commercial ray-trace programs, automated variation of parameters for optical elements is possible and several different metrics can be tabulated vs. the varied parameters. This allows for a fairly straightforward and easy optimization process.

1.2. Program History

RAY was originally written by Jim Houck to run under CP/M machine in the early 1980s. Terry Herter ported the program to the PC. Since then both authors have made changes to improve capabilities of RAY. Although not a full-scale professional ray tracing program, RAY is very capable. Currently RAY only works under MS-DOS. You must run it in a full-screen MS-DOS window if running under Windows 3.1 or Windows 95. A second limitation is that only HP Laserjet II compatible printers are supported. (Non-postscript HP Laserjet III, IV and V printers should work fine.)

One of these day we may port it over to Windows.

2. PROGRAM STRUCTURE

2.1. Overview

The program is menu driven. The main menu consists of single letter commands which are executed as soon as they are typed. All other menus use two letter commands. You must type a <return> for them to be executed. In some cases you can string commands together and they will be executed sequentially.

2.2. Main Menu

The program comes up displaying the main menu from which you can select a number of options to setup the prescription for the optical system, the input ray(s) and to save and/or list the data for future reference. The main menu appears as follows:

```
RayTrace - Version 6.31 (23-Feb-93)
James R. Houck and Terry Herter

Options:

F : Fetch Prescription           M : Modify Prescription
S : Save Prescription           I : Initialize

D : Directory                   C : Color Selections
P : Print Prescription          O : Order Coord Transforms

T : Trace                       V : View Prescriptions
B : File to write trace info (None)
Q : Quit

Current (None)

Select :
```

Figure 1 : Main Menu

A quick description of each of the command is contained in Table 1. This menu is used mainly for input/output from RAY. Most of the action will occur in the "Trace" routines.

Table 1 : Main Menu Command Descriptions

Command		Description
F	Fetch prescription from disk	Read back a prescription that has been save on disk. The filename format is (drive:) filename.ext.
S	Save prescription to disk	Save the current prescription to a disk file named (drive:) filename.ext. You can overwrite a previous version of the same name by typing Y when asked if wish to overwrite. The setup data for tracing rays is also saved in the same file. Save your prescription before tracing. It could bomb and you could loose it!
M	Enter or Modify Prescription	This allows you to enter data on the optical system from the keyboard.
I	Initialize parameters	This erases all information about the current prescription and the setup. All is lost in a flash if you haven't saved the prescription using S.
D	Directory	Will display the directory on a specified drive. No wildcards are supported.
P	Print prescription	This generates a convenient listing of the prescription on a printer or as a disk file (named FILENAME.LIST) for later printing.
C	Color selection	Set colors for text and graphics modes. The file, COLOR.SAV will be saved in the directory in which you are working with the colors you select. When restarting the program from the same directory the colors you have chosen will be restored.
O	Order Coordinate Transformations	Change the order in which coordinate transformations are performed. You can also list the element coordinates from this menu.
T	Trace a ray bundle	This is the section that draws spot diagrams and calculates RMS image size and focus information. This section can also trace single rays. Meridional ray traces can also be done to evaluate the Seidel aberrations.
B	File for trace info	This is a file into which the trace data from RAY can be dumped for later analysis by the user, such as reading into AUTOCAD to display the ray in an optical system drawing.
V	View Prescriptions	Quick viewing of saved ray trace files.
Q	Quits	All unsaved data is lost.

2.3. Prescription Menu

This routine allows the optical prescriptions of the various optical elements to be specified. A sample prescription screen along with a detail discussion is given in the following pages.

```

SN: Surface No. .... 1          NA: Name ..

RA: Radius (0 for flat) .    10.00000    AP: Aperture .....    2.00000
EC: Eccentricity .....    0.00000    FT: Following Thickness .    0.30000

      Indices                Aconics                Tips
-----
FI: Follow'g    1.50000    FA: Fourth ..    0.00000    AT: Alpha ...    0.00000
SI: Short ...   1.52000    SA: Sixth ...   0.00000    BT: Beta ....   0.00000
LI: Long ....   1.48000    EA: Eighth ..   0.00000    GT: Gamma ...   0.00000

      Decenters              Spec. Surface              Miscellaneous
-----
XD: X-Decntr    0.00000    SS: Special Conic Surf    NS: Next Surface
YD: Y-Decntr    0.00000    S1: Coef'nt1    0.00000    PS: Prev. Surface
ZS: Z-Shift     0.00000    S2: Coef'nt2    0.00000    AD: Add Surface
                S3: Coef'nt3    0.00000    DE: Delete Surface
                PN: Prescript Name
                EM: End Mods

Select :
```

Figure 2 : Prescription Menu

Table 2 : Prescription Menu Command Descriptions

Command	Description
SN	Surface Number of the active surface You can call up another surface by changing SN or move to the next surface by typing NS (Next Surface).
NA	surface NAME This is to help you to remember what a given element does e.g.. PRIMARY etc.
RA	Radius of curvature of the surface RA < 0 Center of curvature is to the left of the vertex RA = 0 flat surface RA > 0 Center of curvature is to the right of the vertex
EC	Eccentricity of the surface EC = 0 for a sphere 0 < EC < 1 for an ellipse EC = 1 for a parabola EC > 1 for a hyperbola
AP	Aperture Diameter optical element AP[2] = 0 Aperture is circular with diameter = AP[1] AP[2] <> 0 Aperture is rectangular. Width = AP[1], Height = AP[2]
FT	Following Thickness The distance along the optical axis from the vertex of one surface to the vertex of the next surface.

		FT < 0 If the ray is going right to left. FT > 0 If the ray is going left to right.
FI	Following Index The index of refraction following the surface.	FI < 0 If the ray is going right to left. FI > 0 If the ray is going left to right. FI = 0 If the surface is the focal plane. If a ray is to be reflected at a particular surface the sign of the index changes at the surface
SI, LI	Short and Long refractive Indices	Used for evaluating chromatic aberrations. All spot diagrams are centered on the position of the central ray corresponding to the refractive indices given by the FI's. Therefore, any lateral shift for the other colors corresponds to lateral chromatic aberration. A shift in focus corresponds to longitudinal chromatic aberration.
FA, SA, EA, TA	Aconic coefficients	The Fourth, Sixth, Eighth, and Tenth order coefficients for Aconic surfaces i.e. Schmidt plates
AT, BT, GT	Surface rotations	Rotations about the x, y, and z axes, performed in this order. The coordinate system is maintained by rotating the ray before it reaches the surface and de-rotating it after the ray is refracted or reflected.
XD, YD, ZS	Surface translations	X-Decenter, Y-Decenter, and Z-Shift are translations in the x, y and z coordinates. They are applied and removed in the same way as rotations. Translations are applied after rotations. . Note that the z coordinate is set to 0.0 at the vertex of each surface.
SS	Special Surface	Specifies the type of surface. See Table 3 for details.
NS, PS	Next Surface Previous surface	Move ahead or back one surface.
+1, -1	Insert surface Delete surface	Insert a surface before the current one, or delete the current surface. There is no undo procedure.
PN	Prescription Name	Give a name to it all.
EM	Exit Modifications	Exit prescription modifications. To save things permanently, you must save the prescription to disk.

2.4. Special Surfaces

There are a variety of special surface options. For each option, one or more of the special surface coefficients may be applicable.

Table 3 : Special Surface Descriptions

SS	Command	Description
CS	Conic Surface	EC = 0 for a sphere, etc. S1, S2, S3 Have no meaning.
AS	Aconic Surface of revolution.	A Schmidt plate for example. S3 Convergence limit for surface intersection. There is a maximum of 10 iterations. S3 should be ~ 1/4 to 1/20 of the wavelength depending if the surface is refractive or reflective. S3 > 0.
CY	Cylindrical Surface	The cylinder is flat along the +/- Y direction. For other orientations use Gamma Tip to rotate the element about the optical axis. RA is the radius of the cylinder. EC can be non-zero. S1, S2, S3 Have no meaning.
TS	Toroidal Surface	Like a piece cut out of an inner tube. Cuts along the two major axes of the torus are segments of circles. Noncircular curves are not allowed. S1 Radius about x-axis. S2 Radius about y-axis. S3 Convergence limit (see AS above).
DG	Diffraction Grating	The rulings are along the x direction. The dispersion is along the +/- y direction. The grating is tipped by using a nonzero Alpha Tip. S1 Wavelength S2 Order of the grating S3 Groove spacing S1 and S2 are arrays (1..3) which can be used along with FI, SI, and LI to investigate the wavelength dependence, if desired.
CO	Central Obscuration	The can serve as an inner limit to the surface element. An example is the shadow caused by the secondary of a Cassegrain telescope. The indices before and after the obscuration should be the same. RA, EC, etc. have no meaning. S1 S1[2] = 0 Obscuration is circular with diameter

= S1[1]
 S1[2] <> 0 Obscuration is rectangular. Width =
 S1[1], Height = S1[2]

KE	Knife Edge	<p>The knife edge is in the (x, y) plane. It allows rays to pass for $x < 0$.</p> <p>Irrelevant</p>
RG	Ronchi Grating	<p>Blocks for $x \cdot S1 < 0.25$ and $x \cdot S1 > 0.75$</p> <p>S1 Spacing scale factor for Ronchi Grating</p>
CT	Coordinate Transformation	<p>Normally a rotation or tip of an element is offset or tipped. In the case of a coordinate transformation, an actual transformation to a new coordinate system occurs. This can be handy if you want to change to a new system for entering element information (but can be confusing to interpret).</p> <p>S1, S2, S3 Irrelevant</p>
PL	Perfect Lens	<p>The puts in a perfect lens, which will focus light perfectly in the absence aberrations. This is handy to check the performance of collimated light at any given point in a design.</p> <p>S1 Focal length of the lens.</p>
BR	Branch Point	<p>Jump to some other surface. A branch point can be enable or disabled to change the flow of the optical system. (Such as due to a mirror which flips in and out of the optical path.)</p> <p>S1 Go to element S1.</p>

2.5. Tracing Rays

Entering the “T” command from the main menu gets you to the “Tracing” Menu. It looks like this:

```

FI : Field of Object ..... Far Field

DI : Object Distance ..... 0.00000
DX : X Offset (Degrees or Units) .. 1.00000
DY : Y Offset (Degrees or Units) .. 0.00000
SI : Starting Index ..... 1.00000
WC : Wavelength Code (1, 2 or 3) .. 1

NP : Number of Panels ... 1
NR : Number of Rays ..... 20  RP : Ray Pattern ..... Circmscrbd Sqr

BF : Back Focal Distance ..... 19.79998
PS : Plot Scale (Full Range) ..... 0.01000

CR : Central ray      No List
RX : X coord ...    0.00000  RY : Y coord ...      0.00000 (Sngl Ray)

SD : Spot Diagram      MT : Meridional Trace  TS : Trace Save (FALSE)
PA : Plot Again        BE : Bend surfaces      MP : Modify Prescription

SP : System Plot      PO : Parm Optimiz'n    EX : Exit

Select :
```

Figure 3 : Trace Menu

Table 4 : Trace Menu Command Descriptions

Command	Description
FI Far/Near Field	Toggles between far and near field.
DI Object distance	Distance to the object. Applies only to the near field case. This is ignored in the far field case.
DX, Off axis location of the ob- DY ject.	Measured in degrees for the far field case or linear dimensions for the near field case.
SI Starting index	
WC Wavelength Code	The wavelength code to study chromatic aberrations. A value of 1 selects the FOLLOW INDEX for each surface. While 2 selects SI and 3 selects LI.
NP Number of Panels	The number of panels (spot diagrams) to perform. This allows several sets of bundles of rays to be traced through the system at one time, e.g. the four corners of a spectrograph's entrance slit. Typical numbers are 1, 4, 9, 16, etc. Spot diagrams are traces starting at - DX to DX and DY to - DY with increments appropriate for the number of panels chosen.

NR	Number of Rays	The minimum number of rays that will be followed all the way to the focal plane. If there is a lot of obscuration then things will slow down as a large number of rays must be tried before the required number reach the focal plane.
RP	Ray Pattern	Toggles through the list of available input ray patterns. This is the illumination pattern of the first optical element. RR : Random Rays BE : Bull's Eye IS : Inscribed Square CS : Circumscribed Square
BF	Back Focal Distance	The distance from the last element to the focal plane. It follows all of the usual sign conventions for thickness values.
PS	Plot Scale	Sets the scale of the spot diagram. The spot diagram will be in an area 200x200 pixels. This lets you determine the number of units mapped onto this area.
CR	Central Ray List	Toggles listing of central ray data. If you list the data see something you do not like you can elect not to continue with the trace by entering A (for Abort) at the prompt. Only works when NP = 1.
RX, RY	Single ray coordinates	Allows tracing of single rays through the system. If RX and/or RY are non-zero, they are the X and Y coordinates of the single ray as it hits the first surface of the system.
SD	Spot Diagram	Starts the trace and the generation of the spot diagram. Typing the letter "a" (for abort) will abort the ray trace at any time during the plotting.
PA	Plot Again	Re-plot the data from the previous trace. This will allow you to change the scale of the plot or to re-focus the system by changing the back focal distance, BF. This option does not work properly when the number of panels selected is greater than one.
MT	Meridional Trace	Starts the tracing of a meridional fan of rays. This is particularly useful for optimizing an optical system since it allows you to determine the basic aberrations i.e. coma, spherical aberration, astigmatism etc. See Kingslake's Lens Design Fundamentals for examples on using the meridional trace to optimize an optical system.
BE	Bend surface	Allows surfaces to be "bent" together in the optical system.

TS	Trace Save on/off	Toggles a flag to indicate whether to write ray trace information to disk. If TS = true, then the ray information is written to disk. Note: A trace save file must be opened from the main menu.
MP	Modify Prescription	Provides access to the prescription modification routine which was accessible from the main menu. This has already been described in detail in Section 2.3.
SP	System Plot	Shows the ray paths through the optical system in the x-z or y-x plane. Parameters which affect the nature of the system plot are in the Parameter Optimization menu. See section 2.6 for details.
PO	Parameter Optimization	Allows access to commands which can be used to optimize the optical prescription. See section 2.6 for details.
EX	Exit	Exits to the main menu.

2.6. Parameter Optimization Menu

This menu is entered from the “Trace” menu. A number of commands in the “Trace” menu are duplicated here for convenience. Once you are familiar with ray trace, you may want to do most of your work from this menu.

There are several useful commands that can be used to study and optimize the optical system. A system plot (SP) will show you the position of the optical elements and rays passing through the optical system. Specify the starting surface (SS) to determine the surface on which the system plot begins. You can view the illumination of a surface by specifying it with the VI command. When VI is set to a non-zero number the rays intersecting the specified surface are shown in the spot diagram. You can then tell whether the element is size and position properly.

A color plot will trace rays for the three difference refractive index cases (FI, SI, and LI). Note that this command also affects gratings which can have three difference wavelengths and

System Plotting and Parameter Optimization

```

SS : Start Surf .....      1          AX : Ver/Hor Axes .....      Y,z
MA : Magnification ...    1.00        OD : One-D Rays .....      TRUE
ZO : Z-axis offset ...    0.00        OT : Off-axis Tol'nce .... 0.10
FR : Frac. for SD ....    0.25        PS : Plot Scale .....      0.010000

NP : No. of Panels ...     1          SH : Show Spot Dgrm .....  TRUE
NR : No. of Rays .....    20        CR : Cntr Ray List .....  FALSE
NS : No. of Sys Rays .    10        CT : Cntr List Type .....   0

SD : Spot Dgrm   CP: Color Plot   WC : Wvlength Code .....    1
SP : System Plt  LE: List Elmts   VI : View Illumination ...   0
MT : Meridional Trace           MV : Multiple View .....    FALSE

VP : Vary Parameters           ST : Show Sys Plots .....   TRUE
SE : Setup Parameters          LI : List Computed Parm
MR : Matrix Run (1,2) x (3,4)   MP : Modify Prescription

EO:  End Optimization          RE : Refocus SD Plots ....  FALSE
Select :
```

Figure 4 : Parameter Optimization Menu

Table 5 : Parameter Optimization Menu Descriptions

Command	Description
SS Start Surface	Specifies the surface on which to start the system plot. This allows you to have an instrument attached to a telescope (in the optical design) but still be able to get reasonable size system plots of it by starting at the correct surface. Note: when dealing with objects in the far field, always set SS to at least two (otherwise rays are traced from a source a distance DI away from the first surface).
AX Axis Select	Determines whether the display plane for the system plot is the x-z or y-z plane.
MA Magnification	The Vertical/Horizontal scale ratio for the system plot. This allows fat and skinny optical system to be viewed.
ZO Z-axis Offset	
FR Spot Diagram fraction	
OD 1D rays	Plot 1D rays for system plot.
OT Off-axis tolerance	Used to tell whether to graph only 1/2 of a surface (rather than symmetrically about the vertex) in a system plot. This is useful when dealing with off-axis element.
PS Plot Scale	Sets the scale of the spot diagram. The spot diagram will be in an area 200x200 pixels. This lets you determine the number of units mapped onto

		this area.
NP	Number of Panels	The number of panels (spot diagrams) to perform. This allows several sets of bundles of rays to be traced through the system at one time, e.g. the four corners of a spectrograph's entrance slit. Typical numbers are 1, 4, 9, 16, etc. Spot diagrams are traces starting at $- DX $ to $ DX $ and $ DY $ to $- DY $ with increments appropriate for the number of panels chosen.
NR	Number of Rays	The minimum number of rays that will be followed all the way to the focal plane. If there is a lot of obscuration then things will slow down as a large number of rays must be tried before the required number reach the focal plane.
NS	Number of System Rays	Number of rays to use (show) when doing a system plot.
SH	Show spot diagram	Show the spot diagrams when doing a system plot.
CR	Central Ray List	Toggles listing of central ray data. If you list the data see something you do not like you can elect not to continue with the trace by entering A (for Abort) at the prompt. Only works when NP = 1.
CT	Center List type	Increments (modulo 3) type of display for central ray listing. Different parameters are output for the central ray for CT = 0, 1, or 2.
SD	Spot Diagram	Starts the trace and the generation of the spot diagram. Typing the letter "a" (for abort) will abort the ray trace at any time during the plotting.
SP	Spot Diagram	Shows the ray paths through the optical system in the x-z or y-x plane. Parameters which affect the nature of the system plot are in the Parameter Optimization menu. See description at the beginning of this section for further details.
MT	Meridional Trace	Starts the tracing of a meridional fan of rays. This is particularly useful for optimizing an optical system since it allows you to determine the basic aberrations i.e. coma, spherical aberration, astigmatism etc. See Kingslake's Lens Design Fundamentals for examples on using the meridional trace to optimize an optical system.
CP	Color Plot	Steps through all three colors. Make sure that SI and FI, as well as any grating parameters are properly defined, or the program may bomb.
LE	List Elements	List the positions and tips of the optical elements.
WC	Wavelength code	Choose wavelength code for spot diagram and

		system plot. Either 1, 2 or 3 corresponding to FI, SI or LI.
VI	View Illumination Surface	Specifies the surface which is to be viewed. See description at the beginning of this section.
MV	Multiple view	
VP	Vary Parameters	Steps through the parameter changes as specified in the parameter setup routine (SE). Up to 9 different configurations can be looked at with up to 4 parameters changing simultaneously. The current vary parameter menu is executed.
SE	Setup variation parameters	Set up parameters to vary and select which vary plane to use. See section 2.7.
MR	Matrix run	Like the vary parameter routine but does a matrix of up to 9 different configurations with up to 2 parameters changing simultaneously <i>times</i> up to 9 different configurations with up to 2 parameters changing simultaneously. See section 2.7.
ST	Show system plots	Show system plots along with spot diagrams when doing a VP or MR.
LI	List computed parameters	Lists out the parameters as specified in SE and computed during a VP or MR. See section 2.7.
LD	List computed parameters to a file	Same as LI but data is written to a file. You cannot append to a file! For more than one data set write to a new file each time. Old files can be overwritten (a prompt for permission will appear).
MP	Modify Prescription	Provides access to the prescription modification routine, which was accessible from the main menu. This has already been described in detail in Section 2.3.
EO	End Optimization	Exit parameter optimization routine
RE	Refocus Spot Diagram Plots	Specifies whether to refocus each spot diagram (to best focus) during a VP or MR.

2.7. Parameter Variation Menu

This menu allows input of a range of parameters to change. This is a primitive capability to do optimization. This menu is reached through the SE command in the “Parameter Optimization” menu.

You can either step through 9 different configurations while changing up to 4 parameters in each, or you can do a matrix run of up to 9 configurations by 9 configurations while changing two parameters in each. There are 4 different “variation planes” you can set up.

```

Parm Codes   : RA, EC, AP, FT, FI, SI, LI, FA, SA, EA, AT, BT, GT, XD, YD, ZS,
              SS, S1, S2, S3, DL, DN, CU; BE; DX, DY, WC, VI, BF

Save codes   : RMS, Sm_RMS, Delta_z, RMS_x, Sm_RMS_x, Delta_x, RMS_y,
              Sm_RMS_y, Delta_y, RayCnt, Avg_x, Avg_y, Avg_z, Abs_z,
              L-l, D-dDN, D-dDnMax, CRH, RTF, Astig, Coma,
              x_c, y_c, z_c, at (Cx/Cz), at (Cy/Cz), 90-ac (Cx), 90-ac (Cy), ac (Cz)

Cmnd codes   : List, Fill, Vary, Delta, Incr, Help, PR, NR, PC, NC,
              Clr, ClrAll, DefSurf(0), VP(1), NP, PP, Copy, MP, ES

Tbl  ----- 1 ----- 2 ----- 3 ----- 4 -----
1: RA  1    3.00000          0.00000  FI  1    1.50000          0.00000
2: RA  1    4.00000          0.00000  FI  1    1.60000          0.00000
3: RA  1    5.00000          0.00000  FI  1    1.70000          0.00000
4:      0.00000          0.00000          0.00000          0.00000
5:      0.00000          0.00000          0.00000          0.00000
6:      0.00000          0.00000          0.00000          0.00000
7:      0.00000          0.00000          0.00000          0.00000
8:      0.00000          0.00000          0.00000          0.00000
9:      0.00000          0.00000          0.00000          0.00000

List : RA 1 FI 1 RayCnt RMS Sm_RMS

Option :
```

Figure 5 : Vary Parameter Setup Menu

Here we are looking at “variation plane” number 1. The radius of curvature and following index of surface number 1 is being changed. If a “Matrix Run” is performed in the “Parameter Optimization” menu, then there will be 9 spot diagrams forming the product of the changes in columns 1-2 and 3-4. If a “Vary Parameter” is performed, 3 different spot diagrams will be performed. The parameters in the “List” line will be kept for each spot diagram and can be viewed on the screen or dumped to the printer.

3. RAYTRACE OUTPUT FORMATS:

Following an SD command you will get a list of numbers (the path of the central ray through the system) if the listing option is turned on. As discussed above you can elect to abort the trace at this time. If the trace is continued a spot diagram will be generated and displayed next. For the case NP = 1, you will get a page showing the results of the trace after the graphics output like that shown below. The top row of numbers gives the average position of the rays in the focal plane.

```
File : CASS.RAY      Name: Cassegrain Telescope

Average Spot Position: X =  -0.209544  Y =   0.419090

Central Ray Values:
X =  -0.209451  Y =   0.418904  Z =  -0.000000
Cx =  -0.006046  Cy =   0.012092  Cz =   0.999909

Spot Statistics: ( 81 rays traced in 128 tries) :
RMS   = 0.000471  Sm_RMS   = 0.000195  Delta_Z  = -0.014405
RMS_X = 0.000288  Sm_RMS_X = 0.000116  Delta_Zx = -0.012509
RMS_Y = 0.000373  Sm_RMS_Y = 0.000146  Delta_Zy = -0.016300

Circumscribed grid pattern traced.

Do you want to refocus?
 1 - To the minimum RMS
 2 - To the minimum RMS_X
 3 - To the minimum RMS_Y
   - Any character for not refocus

Select :
```

The central ray data lists the coordinates of the central ray (the one going through the center of the first surface) in the focal plane relative to the geometric axis of the system. Note: the focal plane can be tipped, curved, figured etc. just like any other surface. Note too: central rays have the ability to go through an obscuration. The spots on the spot diagram are plotted relative to the location of the central ray. The direction cosines are also listed for the central ray.

A line giving the number of rays reaching the focal plane and the number of rays tried is displayed next. You can get a rough idea if one or more of the elements is too small by looking at these statistics. A better way is described above under the FI section of option P.

Next come three lines each listing the RMS spot size, the smallest RMS spot size (assuming you refocus the system) and the required shift in focus to reach the smallest spot size. You are then asked if you wish to refocus and if so to the smallest total RMS, to the smallest RMS in the X direction or to the smallest RMS along the Y direction. When NP > 1 a different statistical display appears. In this case a summary is given for each set of rays traced. An example for NP = 9 is shown below. The columns are pretty much self-explanatory in that they follow the description given above for NP = 1.

File : CASS.RAY Name: Cassegrain Telescope
 Panel Mode: 9 panels computed.

128 rays attempted in circumscribed grid pattern.

	DX	DY	NumRays	Avg. X	Avg. Y	Z-Center	RMS	Delta Z
1	-0.100000	0.200000	81	-0.209544	0.419090	-0.000000	0.000471	-0.014405
2	0.000000	0.200000	81	-0.000000	0.419086	0.000000	0.000383	-0.011525
3	0.100000	0.200000	81	0.209544	0.419090	-0.000000	0.000471	-0.014405
4	-0.100000	0.000000	81	-0.209536	-0.000000	0.000000	0.000116	-0.002882
5	0.000000	0.000000	81	-0.000000	-0.000000	0.000000	0.000000	-0.000000
6	0.100000	0.000000	81	0.209536	0.000000	0.000000	0.000116	-0.002882
7	-0.100000	-0.200000	81	-0.209544	-0.419090	-0.000000	0.000471	-0.014405
8	0.000000	-0.200000	81	-0.000000	-0.419086	0.000000	0.000383	-0.011525
9	0.100000	-0.200000	81	0.209544	-0.419090	-0.000000	0.000471	-0.014405

Done with Stats
 Press <cr> to continue

A sample meridional trace output for the on-axis case is shown below. This will give information on spherical and chromatic aberration.

```
On-axis aberrations:
L - l                = -0.0000046072
D - d delta n       = 0.0000000000
D - d delta n Max   = 0.0000000000
```

Press <cr> to continue

When an off-axis meridional trace is performed, the off-axis aberration coefficients are included.

```
On-axis aberrations:
L - l                = -0.0000046072
D - d delta n       = 0.0000000000
D - d delta n Max   = 0.0000000000

Off-axis aberrations:  Off-axis distance/angle = -0.10000
Chief ray height      = -0.20944
Radius tan field      = -9.74815
Astigmatism           = -0.00127
Coma                  = 0.00044
```

Press <cr> to continue

3.1. A Note on Dimensions

You are free to use any type of linear dimensions you like i.e. cm or inches but you must be consistent. In the special case of diffraction gratings you must use the same linear dimensions for the wavelength and the groove spacing but these need not be the same units as for thicknesses etc.

All angular measures must be in degrees.

3.2. Hard Copies

The spot diagram, system plot, and meridional trace plots are finished when "Done" is displayed on the screen. At this time, if you have an HP Laserjet compatible printer you can make a hardcopy by entering the letter "P" or "H". Note that the capitalization is necessary (to prevent accidental hardcopies). The "P" option dumps the screen and then delivers a formfeed to the printer while the "H" option only dumps the screen.

The "H" command is handy because when the statistics screen is displayed you can then do a <shift>PrntScr (in the usual DOS way) to tack the statistics onto the spot diagram. After returning to the trace menu, you can eject the page on the printer with the FF (formfeed) command. This command is NOT listed on the menu but is nonetheless very useful at times.

If you do not have an HP Laserjet compatible printer you will have to supply your own graphics dump program (which is loaded before running RAY) to make hardcopies.

4. REVISION HISTORY

This documents changes between versions. Unfortunately it was only started very recently.

Version	Date	Comments
6.31	03-Feb-97	
6.40	27-Sep-97	Not sure - May have introduced a bug here on startup. The message is divide by zero. It occurs sporadically. Make sure the EGAVGA.BGI file is in the same directory as the executable. Also try deleting ray.def file and restarting.
6.50	05-Mar-00	Added "LD" command to list parameter variation output to a text file. Fixed bug in "10 th aconic" printing.
6.60	25-Oct-01	Fixed problem with fast PC that caused programs to crash at start. This was a Borland library routine problem.

5. APPENDIX I: CASSEGRAIN EXAMPLE

This appendix show an example set of outputs for a Cassegrain Telescope.

A summary of the prescription (using the "P: Print" command and directing the output to a file) is shown below:

```
File : RAY.DEF          Name : Cass Example          Page 1

Surface Number ..      1          2          3
Name .....           Primary   Secondary Focal Plan
Radius .....         -60.000000 -18.666600  0.000000
Eccentricity ....     1.000000   1.666660   0.000000
Aperture .....        10.000000   3.000000   1.000000
Follow. Thckns ..    -23.000000  28.000300   0.000000

Follow. Index ...     -1.000000   1.000000   0.000000
Short Index .....     1.000000   1.000000   1.000000
Long Index .....      1.000000   1.000000   1.000000

Fourth Aconic ...     0.0E+0000   0.0E+0000   0.0E+0000
Sixth Aconic ....     0.0E+0000   0.0E+0000   0.0E+0000
Eighth Aconic ...     0.0E+0000   0.0E+0000   0.0E+0000
Tenth Aconic ...      0.0E+0000   0.0E+0000   0.0E+0000

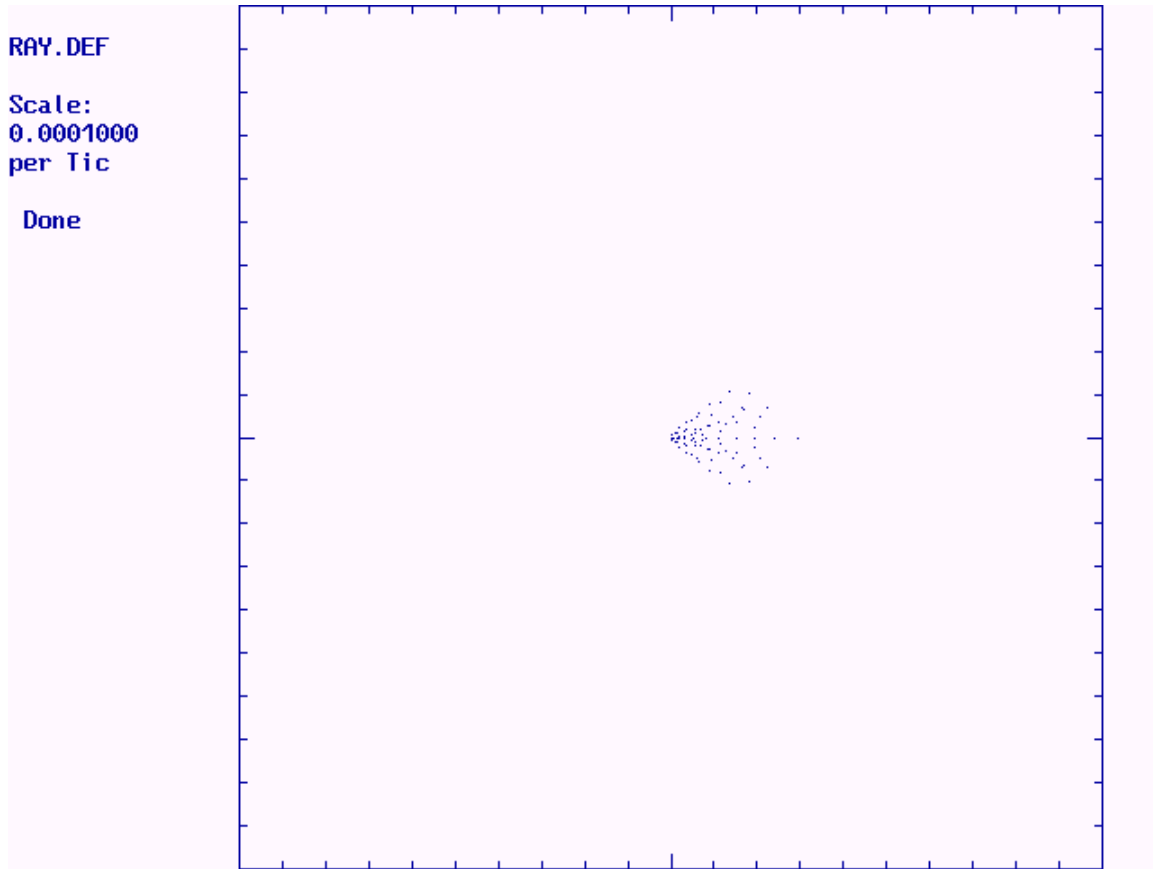
Alpha Tip .....       0.000000   0.000000   0.000000
Beta Tip .....        0.000000   0.000000   0.000000
Gamma Tip .....       0.000000   0.000000   0.000000

X-Decenter .....     0.000000   0.000000   0.000000
Y-Decenter .....     0.000000   0.000000   0.000000
Z Shift .....        0.000000   0.000000   0.000000

Sp. Surface .....    Conic Surf  Conic Surf  Conic Surf
Sp. Coef1. ....      0.000000   0.000000   0.000000
Sp. Coef2. ....      0.000000   0.000000   0.000000
Sp. Coef3. ....      0.0E+0000   0.0E+0000   0.0E+0000
```

The next two pages show spot diagrams for the case of number of panels (NP) equal 1 and 9 respectively. For NP = 1, the source is at DX = 0.1 and DY = 0.0 degrees. For NP = 9, the source is varied in a grid from DX = -0.1 and DY = 0.2 to DX = 0.1 and DY = -0.2. System plots are shown for each on the third page.

Spot diagram for NP = 1 and DX = 0.1. The system has been focused to the best rms at this position.



File : CASS-EX.RAY Name: Cass Example

Average Spot Position: X = 0.209519 Y = -0.000000

Central Ray Values:

X = 0.209426 Y = 0.000000 Z = 0.000000
Cx = 0.006046 Cy = 0.000000 Cz = 0.999982

Spot Statistics: (81 rays traced in 128 tries) :

RMS = 0.000079 Sm_RMS = 0.000079 Delta_Z = -0.000000
RMS_X = 0.000066 Sm_RMS_X = 0.000065 Delta_Zx = -0.000632
RMS_Y = 0.000042 Sm_RMS_Y = 0.000040 Delta_Zy = 0.000632

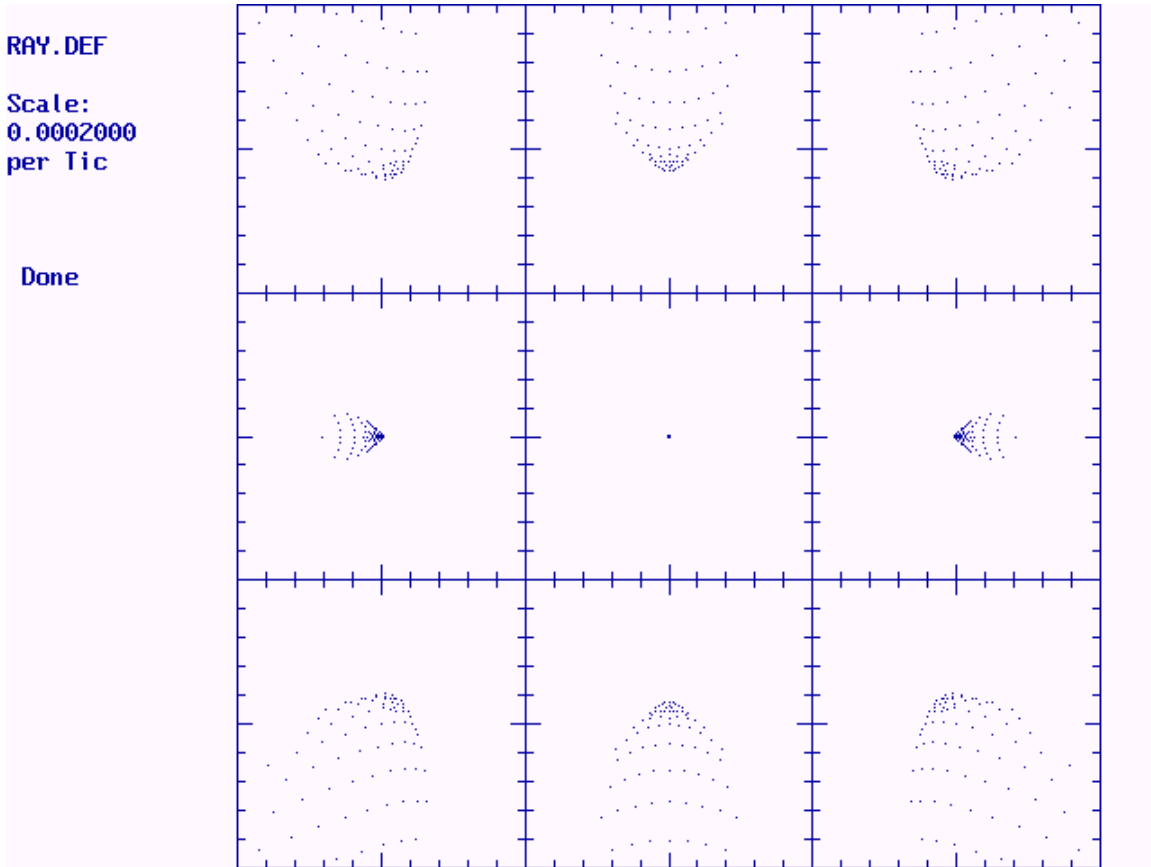
Circumscribed grid pattern traced.

Do you want to refocus?

- 1 - To the minimum RMS
- 2 - To the minimum RMS_X
- 3 - To the minimum RMS_Y
- Any character for not refocus

Select :

Spot diagram for NP = 9, DX = -0.1, and DY = 0.2. The system has been focused at DX, DY = 0

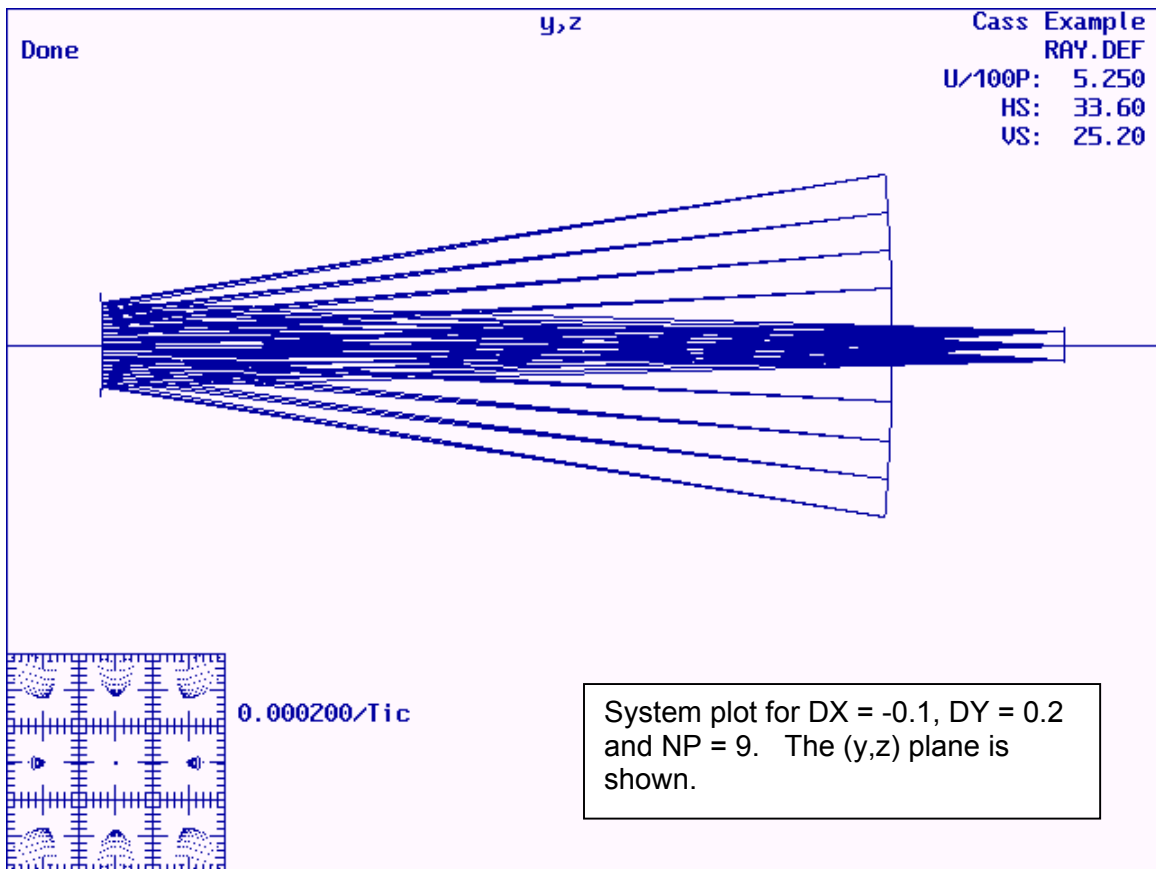
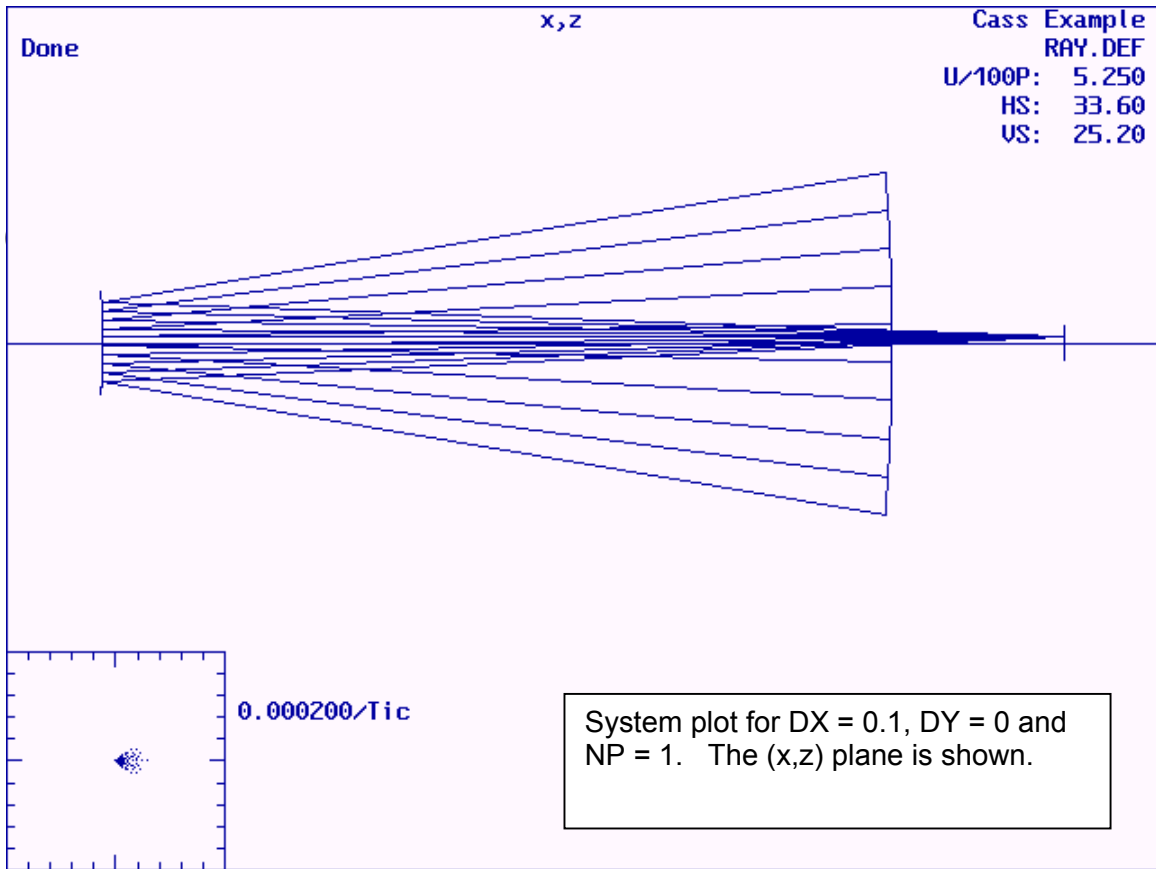


File : RAY.DEF Name: Cass Example Panel Mode: 9 panels computed.

128 rays attempted in circumscribed grid pattern.

	DX	DY	NumRays	Avg. X	Avg. Y	Z-Center	RMS	Delta_Z
1	-0.100000	0.200000	81	-0.209544	0.419090	0.000000	0.000471	-0.014406
2	0.000000	0.200000	81	0.000000	0.419086	-0.000000	0.000383	-0.011526
3	0.100000	0.200000	81	0.209544	0.419090	0.000000	0.000471	-0.014406
4	-0.100000	0.000000	81	-0.209537	-0.000000	0.000000	0.000116	-0.002883
5	0.000000	0.000000	81	-0.000000	-0.000000	0.000000	0.000000	-0.000001
6	0.100000	0.000000	81	0.209537	-0.000000	0.000000	0.000116	-0.002883
7	-0.100000	-0.200000	81	-0.209544	-0.419090	0.000000	0.000471	-0.014406
8	0.000000	-0.200000	81	0.000000	-0.419086	-0.000000	0.000383	-0.011526
9	0.100000	-0.200000	81	0.209544	-0.419090	0.000000	0.000471	-0.014406

Done with Stats
Press <cr> to continue



APPENDIX B: A RAYTRACE TUTORIAL

This appendix is a step-by-step guide to entering and analyzing a simple prescription using the RayTrace program. The user should follow it as he or she sits at the computer. For more detailed information on operation and options with RayTrace, see the documentation.

This example examines the 24-inch Hartung-Boothroyd Observatory on Mt. Pleasant. In the following, all distances are in centimeters, and the rays travel primarily along the z-axis.

Before starting up the program make sure there is a copy of the EGAVGA.BGI file in the directory in which you are working. To start the program, type **ray** at the DOS prompt. The main menu will be displayed, indicating no current prescription.

Entering the Optical Prescription

Type **M** to input the prescription. The program will display the prescription menu for Surface No. 1. To input parameters for the surfaces, type

na	Primary	(name of this surface)
ra	-500.8	(negative because the center of curvature is a negative z-distance from the vertex)
ec	1.0	(eccentricity of a paraboloid)
ap	62.2 0.0	(a 24-inch circular aperture. Enter 0.0 for the second aperture setting. This would be nonzero for a rectangular aperture.)
ft	-177.96	(negative z-distance to the vertex of the next surface)
fi	-1.0	(index of refraction changes sign on reflection)
ns		(go to next surface)
na	Secondary	
ra	-207.9	
ec	1.87	
ap	20.0 0.0	
ft	238.97	
fi	1.0	(another reflection)
ns		(go to next surface)
na	Focal Plane	
pn	HBO Tel.	(to name the entire prescription)
em		(exit prescription menu and go to main menu)

Note that nearly all of the parameters for the last surface can be left at their default values – it is only necessary that **fi** be set to 0.

This is a good time to save the prescription to disk by selecting the S option from the main menu. Only the filename needs to be specified (limited to 8 characters) – **.ray** will be automatically appended.

Tracing

Enter T to get to the tracing menu. There are several parameters that need to be checked.

fi	Far Field	(incoming rays are parallel)
si	1.0	(starting index of refraction)
di	100.0	(not critical in the far field)
nr	100	(rough number of rays to trace)
np	1	(just one panel for now)
ps	0.0025	(25 microns, the size of one pixel in the HBO CCD camera)
wc	1	(wavelength code)

Now you are ready to trace rays. To trace rays through the system and look at a "spot diagram" (a plot of the ray intersections with the last surface), type **sd**. Hitting the carriage return displays another menu listing statistics and options for focusing. Comparing the rms spot size with the smallest possible rms shows that focusing is necessary. Pressing **1** changes the back focal distance (really the following thickness for surface 2), and returns to the tracing menu. To see a new plot do **sd** again. The spot should now be a well-focused point.

To get an idea of what the optical system looks like, do a system plot. **sp** displays a view of the rays with the z-axis running horizontally and the y-axis running vertically.

Off-axis Rays

A common use of RayTrace is to evaluate off-axis aberrations. An example is finding the aberrations at the edge of the HBO CCD camera. This instrument has a field of view of 4 arcmin by 6 arcmin, so to put in a ray at the longest edge, set **dx** = 0.05 degrees (which is 3 arcmin), and type **sd** for a spot diagram. You should see the fan-like shape characteristic of coma -- but note that it is much smaller than one pixel (the extent of the plot, as set by **ps**).

To trace rays to all four corners of the array, set **dy** to 0.033 (2 arcmin) and **np** to 9. This will trace rays incoming at angles of +2, 0, and -2 arcmin in the y-direction and +3, 0, and -3 along x. Entering **sd** produces an interesting plot.

Adding a Few Complications

In a real Cassegrain telescope, the secondary mirror obscures part of the primary. We can simulate this effect by adding a new surface. Enter the prescription modification menu (you can do this from the "tracing" menu with the **mp** command) and move to the first surface (you will probably need to use the **ps** [previous surface] command), then type

ad		(insert another surface)
na	Sec. Obs.	(Secondary Obscuration)
ap	62.2 0.0	Again circular
ft	1.0	(rough number of rays to trace)
ss	co	(select a special surface: central obscuration)
s1	20 0.0	(diameter of obscuration, again circular)
em		(End prescription mods. You can use ns and ps to make sure the obscuration was is in the correct place and your other surfaces are okay.)
sd		(Do a spot diagram [still with np = 9].)

You won't notice much difference in the spot diagrams or the statistics listed, except that the number of rays trace through the system at each point is 72 instead of 81 indicating that the obscuration is present.

Viewing Optical Element Illumination

We can look at the illumination of the various elements of the optical system.

rp		(Change the ray pattern to Bull's Eye. Typing rp successive times will cycle through the options.)
po		(Go to the parameter optimization menu)
vi	1	(View the illumination of the telescope, actually the central obscuration surface.)
sd		(A spot diagram now shows the illumination - note that rays uniformly fill the surface in a Bull's eye pattern)
vi	2	(View primary mirror)
sd		(Note the central obscuration! Also each "point" is now fuzzy since we are tracing 9 different incident directions)
vi	3	(View secondary mirror)
sd		(The central hole is still there and the images are now even fuzzier. You can see now that if you made the secondary too small you would vignette the field.)

vi	4	(View the focal plane. This differs from a spot diagram since you see all the spots on one plot.)
sd		(You don't see all the spot in the focal plane! They are vignetted by the (default) aperture size.)
mp		(Modify the prescription.)
ns		(Repeat to move to the focal plane surface)
ap	1.5 1.0	(Set it to be a rectangular aperture)
em		(End prescription mods)
sd		(Now you can view the illumination of the full focal plane.)
vi	0	(Set view illumination back to zero to get a "normal" spot diagram.)
sd		(Take a look at it to see that it's back to normal.)
eo		(Get out of the optimization menu)

Introducing Asymmetries

Thus far the prescription is completely symmetric about the z-axis. A real telescope may suffer from misalignment, or one of the optical elements may be purposely tipped. To simulate misalignment of the secondary, we can rotate this surface about the x-axis by changing **at** (alpha tip) for the secondary to some non-zero value. Try seeing **at = 0.0167** (1 arcmin) for the secondary mirror in the prescription modification menu and do a spot diagram with **dx = dy = 0**, and **np = 1**. The coma caused by this small misalignment should be evident.

In some situations, it may be desirable to the secondary to bring a different part of the sky onto a fixed detector. Moreover, the point about which the secondary is rotated may not be its vertex. To simulate a tip about another axis, we want to tip the secondary about its vertex, then decenter it. For example, the optimum point in a classical Cassegrain about which to tip the secondary is the focal point of the primary. Set **at = 0.0167** and **yd = 0.021** to simulate such a rotation. A spot diagram with **dx = dy = 0** should be much improved -- but this no longer hits the center of the focal plane.

Can you find **dy** such the spot diagram for the tip, decentered secondary hits the center of the focal plane? (Hint – look at average spot position in the spot diagram statistics).