

Lesson 4: The Amateur Telescope

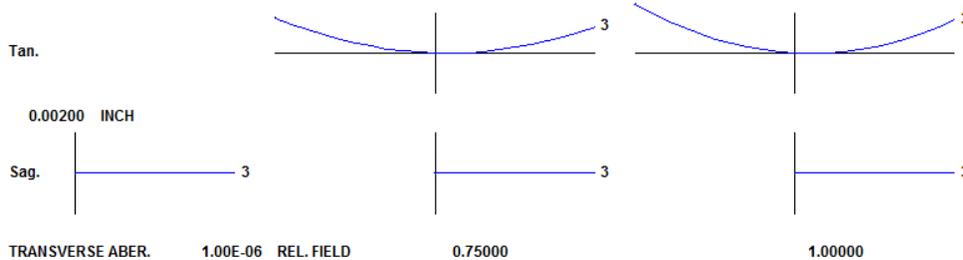
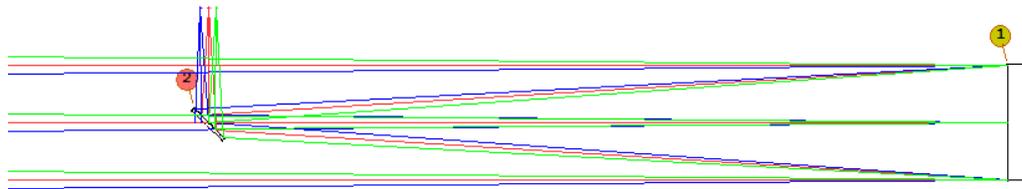
This lesson is intended for those interested in designing or analyzing the kind of small telescopes popular with amateur astronomers.

The Newtonian Telescope

Probably the most popular kind of amateur telescope is the Newtonian, about the simplest system there is except for a shaving mirror. Here is the input RLE file for a typical telescope:

```
RLE
ID F/8 PARABOLA WITH DIAGONAL MIRROR
WAVL .6562700 .5875600 .4861300
APS 1
GLOBAL
UNITS INCH
OBB 0.000000 0.50000 5.00000 0.00000 0.00000 0.00000 5.00000
MARGIN 0.050000
BEVEL 0.010000
0 AIR
1 RAD -160.000000000000 TH -70.00000000 AIR
1 CC -1.00000000
1 AIR
1 EFILE EX1 5.050680 5.050680 5.060680 0.000000
1 EFILE EX2 4.900000 4.900000 0.000000
1 EFILE MIRROR 2.000000
1 REFLECTOR
2 EAO 1.34300000 1.90000000 0.00000000 -0.10000000
2 CV 0.000000000000 TH 0.00000000 AIR
2 AIR
2 DECEN 0.00000000 0.00000000 0.00000000 100
2 AT 45.00000004 0.00000000 100
2 EFILE EX1 1.950000 1.950000 1.960000 0.000000
2 EFILE EX2 1.950000 1.950000 0.000000
2 EFILE MIRROR -0.300000
2 REFLECTOR
3 CV 0.000000000000 TH 10.00000001 AIR
3 AIR
3 DECEN 0.00000000 0.00000000 0.00000000 100
3 AT 45.00000004 0.00000000 100
3 TH 10.00000001
3 YMT 0.00000000
4 CV 0.000000000000 TH 0.00000000 AIR
4 AIR
END
```

Here is the system, shown by the PAD display:



The field of view was set at $\frac{1}{2}$ degree from the axis by the OBB line:

OBB 0.00000 0.50000 5.00000 0.00000 0.00000 0.00000 5.00000

where the arguments are

```
OBB ump0 upp0 ymp1 [ yp1 uxp0 xp1 xmp1 ]
```

To show this information in the TrayPrompt, simply *select* the characters “OBB” in the editor. The program then looks up the format for you. In this input,

- ump0 is the incident marginal ray angle, zero for an object at infinity. (The OBB format is used mostly for that situation.)
- upp0 is the incident chief-ray angle, here 0.5 degrees
- ymp1 is the incident marginal ray height, here 5 inches, making a 10-inch diameter entering beam.

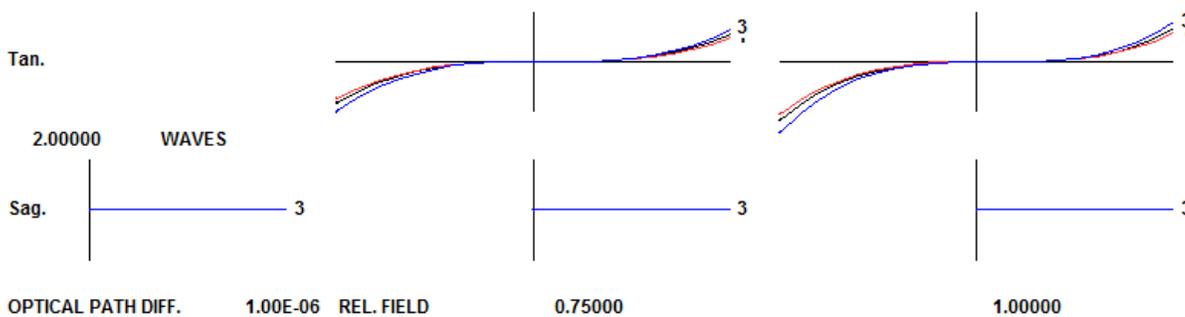
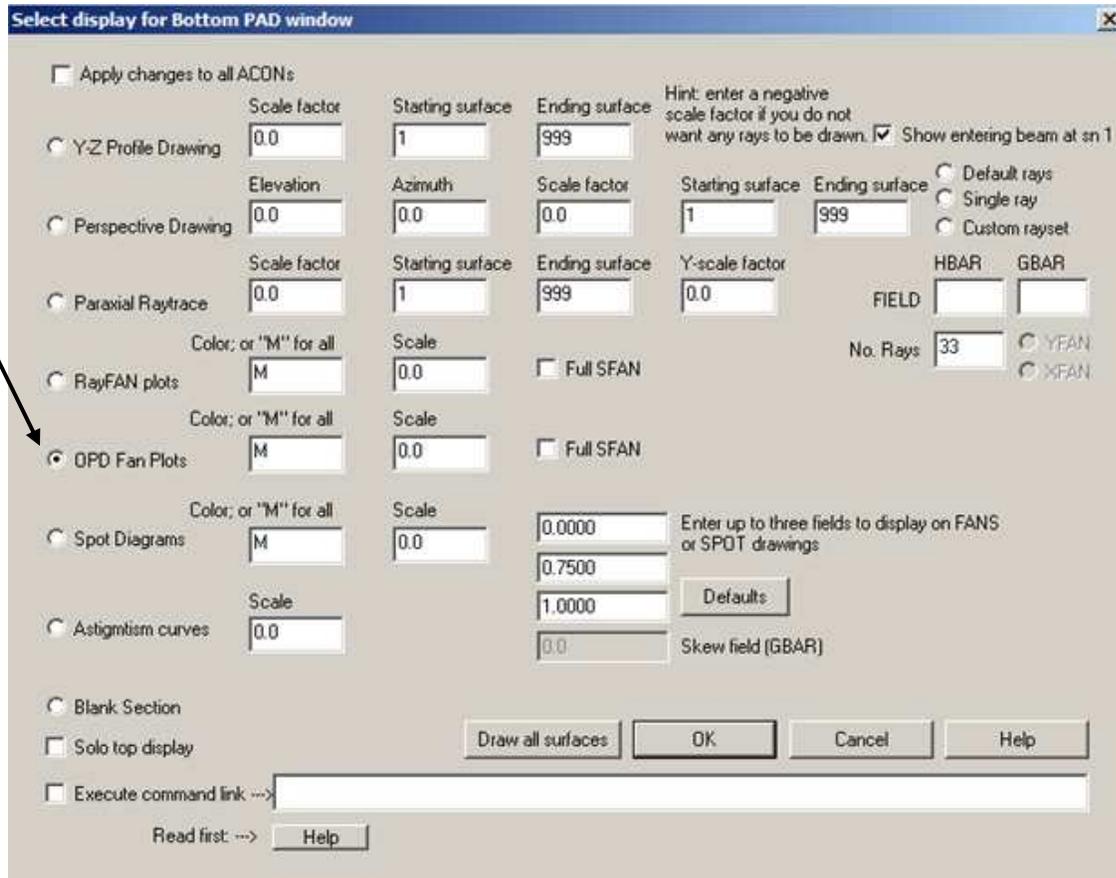
The other arguments are all irrelevant here; yp1 is the chief-ray height on surface 1, zero since that is the stop, and the rest refer to the X-Z plane, which we ignore since the input is axially symmetric. If you’re confused already, just open the Object Wizard¹ (**MOW**) to see everything spread out and explained for you there.

The RLE input is designed to be easy to read without any explanation. Surfaces 1 and 2 are declared reflectors, the conic constant on the primary mirror is -1.0, making it a paraboloid. The **EFILE** data are somewhat cryptic, however; those data are used to define the edge geometry of lenses, and for mirrors the substrate thickness. That makes no difference in the raytrace, of course, but a proper edge makes a nice picture and is important if you want to make drawings of the mirror for the shop. We will discuss that topic in more detail in lesson 23.

Let us note that the above file is produced in response to the command **LEO** (**LEns Out**) or **LE** (**LEns Edit**) and contains a complete description of the system, including all of the defaults – which you could leave out if you want to enter the data yourself. In that case, the file would be much shorter.

¹ Object Wizard™ is a trademark of Optical Systems Design, Inc., a Maine, USA corporation.

The image is, of course, perfect on axis, but there is lots of coma, which is a well-known defect of this simple system. How serious is that coma? In PAD, select view 2, (click that number in the PAD toolbar ) and then click the PAD Bottom button . In the dialog that opens, select the OPD Fan Plots option and then OK.



Yes, there appears to be about two waves of coma at the edge of the field.

Here is how to get a listing:

```

SYNOPTSYS AI>OPD           ! The next command will be in OPD mode
SYNOPTSYS AI>TFA 5 P 1     ! tangential fan, five rays, primary color, full field
ID F/8 PARABOLA WITH DIAGONAL MIRROR

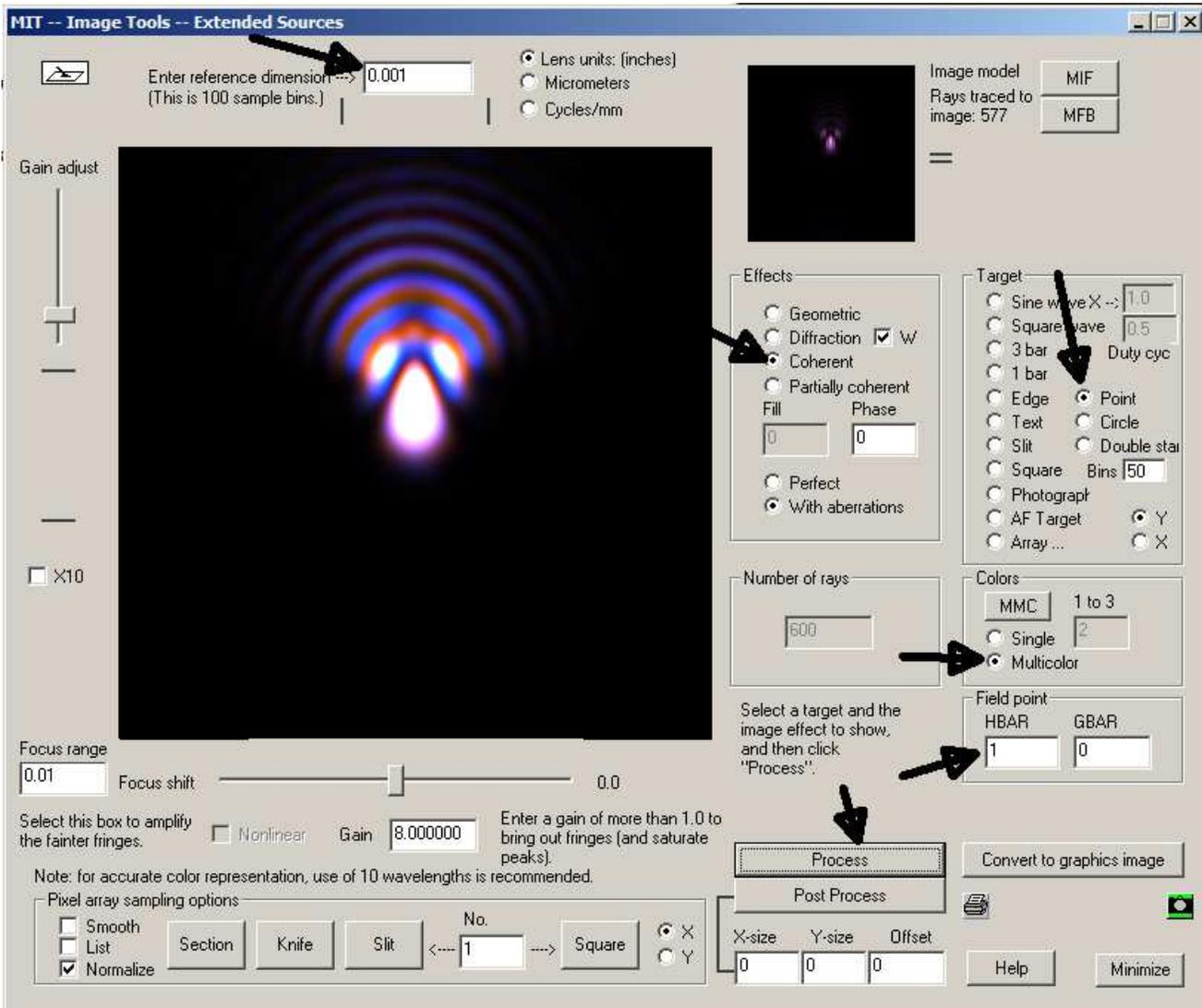
```

TANGENTIAL RAY FAN ANALYSIS

FRACT.	OBJECT HEIGHT	HBAR	1.000000	GBAR	0.000000
COLOR NUMBER		2			
REL ENT PUPIL YEN	WAVEFRONT ABERR OPD (WAVES)				
-1.000	-2.355059				
-0.800	-1.271960				
-0.600	-0.583027				
-0.400	-0.200234				
-0.200	-0.035356				
0.200	-0.005883				
0.400	0.035526				
0.600	0.212506				
0.800	0.613233				
1.000	1.325667				

As usual, you can get the same thing without typing the command yourself if you want to. Go to the dialog **MRR** (Menu, Real Rays) or navigate the menu tree, and make your selection there. In this case, typing the command is actually faster, so we chose to do it that way.

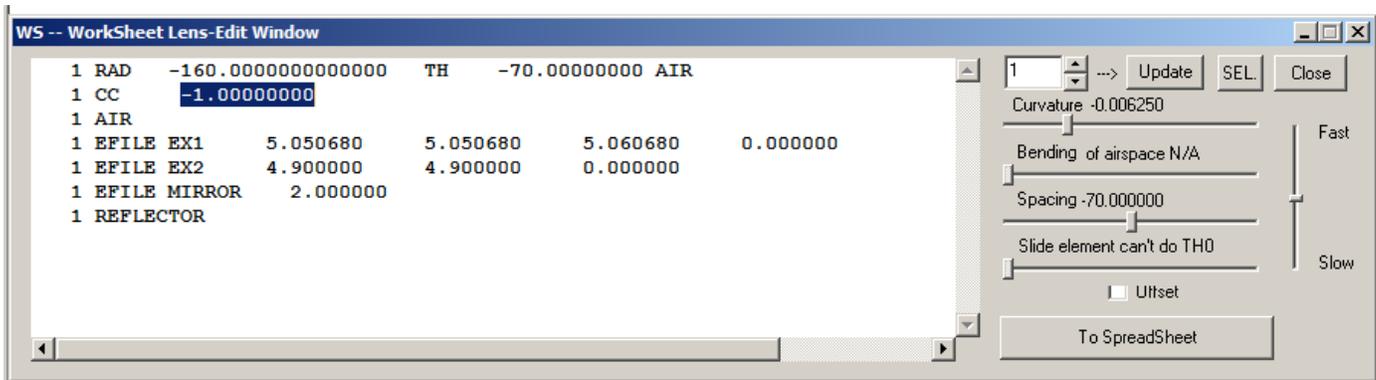
Let's look at that image in some detail. There are several tools for the purpose, but we like the Image Tools (MIT) dialog. Type **MIT**, and then make the selections shown below.



This is a rather beautiful example of third-order coma.

Just for fun, try this with the Geometric, and then Diffraction, selection in the Effects section. The Coherent analysis is somewhat smoother. It uses a 2-D FFT algorithm, while the Diffraction method evaluates the diffraction integral, clipping at about 6 times the radius of the Airy disk. This image is slightly larger than that, and a point source is always coherent with itself – so the coherent choice is generally best for a point source and definitely better here.

How does the image quality vary with the value of the conic constant? SYNOPSIS can answer questions of this sort very well. In PAD, click the Checkpoint button, , and then go to the WorkSheet. Click on surface 1 (or enter that number in the number box and click Update). Now, with the mouse, *select* the *entire* number giving the conic constant:



and then click the **SEL** button. The top slider now controls that string of numbers. Slowly drag it to the left and right, watching the PAD display. These sliders give you a wonderful way to evaluate the effects of changing nearly anything in the lens.

We will now evaluate the image quality on axis. Here we will use a different tool – but first we need to tell the program about the obscuration, which was not given in the input file. With WS still open, type into the edit pane

```
1 CAI 1.4
```

and then click the Update button. (CAI means Clear Aperture, Inside.) Now, a hole shows up in the primary mirror. Click the Checkpoint button again. (We click it whenever we have made a change that we might want to go back to.) Type **CAP** in the CW, and you see the CAI data listed:

```
SYNOPSIS AI>CAP
```

```
ID F/8 PARABOLA WITH DIAGONAL MIRROR
```

```
CLEAR APERTURE DATA
(Y-coordinate only)
```

SURF	X OR R-APER.	Y-APER.	REMARK	X-OFFSET	Y-OFFSET	EFILE?
1	5.0007		Soft CAO			*
1	1.4000		*User CAI			*
2	1.3430	1.9000	*User EAO	0.0000	-0.1000	*
3	1.2378		Soft CAO			
4	0.7006		Soft CAO			

```
NOTE: CAO, CAI, EAO, and EAI input is semi-aperture.
      RAO and RAI input is full aperture.
SYNOPSIS AI>
```

This system has mostly default apertures, although there is now a user-entered inside aperture (a CAI) on surface 1 along with the outside elliptical aperture (EAO) on surface 2, the diagonal mirror. (The menu **MLL** (Menu, Lens Listings) also lets you run the CAP command.) Let's create a footprint on the primary mirror. Navigate with the menu tree to MFP (or type **MFP** in the CW). Make the selections below and click Execute.

MFP -- Footprint Plots

OBS Norm. Position: 0 Norm Radius: 0

Check this option to mask the entering beam with a circular obstruction. Parameters are fractional position (in Y) and fractional obscuration. You don't need this option if your obscuration is given by CAI data in the lens.

Select Ray Pattern in Pupil

PUPIL Selection: 20

Connect raypoints with line (PUPILS 3 and 4 only)

PUPIL 1: Rectangular raygrid

PUPIL 2: X-Rayfan

PUPIL 2: Y-Rayfan

PUPIL 3: Circle expands to meet clear apertures

PUPIL 4: Circle, shrinks to fit in CAOs

Select Surface for Footprint Plot

Surface Number: 1 Scale X Times: 5 X-Position: 0 Y-Position: 0

Center at ---> Center at Chief Ray

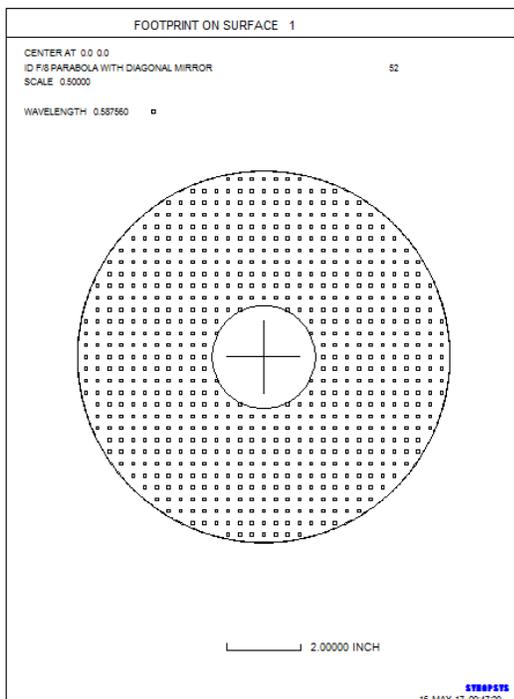
Select Object Points and Colors

TRACE	Color number (1 to 3)	HBAR Fractional Y-Field	GBAR Fractional X-Field	Number of Rays	
<input type="checkbox"/>	P	0	0	800	First object point to trace
<input type="checkbox"/>	P	0	0	20	Check these to trace up to 4 additional object points.
<input type="checkbox"/>	P	0	0	20	
<input type="checkbox"/>	P	0	0	20	
<input type="checkbox"/>	P	0	0	20	

Execute

Cancel

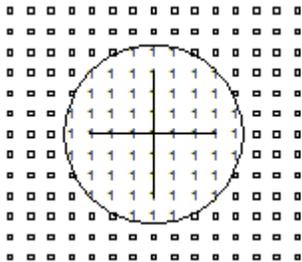
Help



Now you see the inside aperture, which is free of rays. Here's a neat trick: suppose you don't know where the rays are being vignetted (that happens sometimes with complex lenses). Here's how to find out: First hit the <Enter> key (when you have used a dialog to run anything, you go right back there. That's a time-saver). Now, click the Switches button

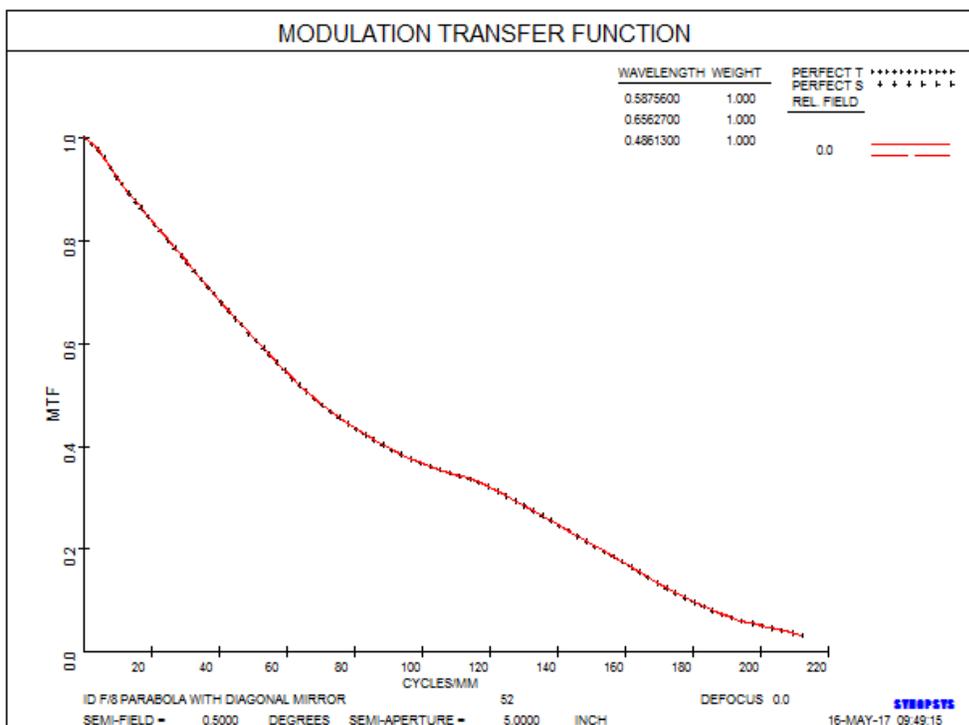


, and click the radio button to turn on switch 21. SYNOPSIS™ has almost 100 mode-control switches, and this one causes several features to display the surface number where a ray stops. Click Apply, and then run the footprint command again. It makes a new picture, and in the center we see:



The numeral "1" now shows up where each vignetted ray would have been.

Okay, it's time for some image analysis. Go to the MOP dialog, either with the menu tree or with the command **MOP** (**M**tf **O**ptions). Select the Multicolor option for the MTF, and click the MTF button.



The obscuration has indeed produced a dip in the MTF at mid frequencies, as everyone already knows should happen with a Newtonian telescope.

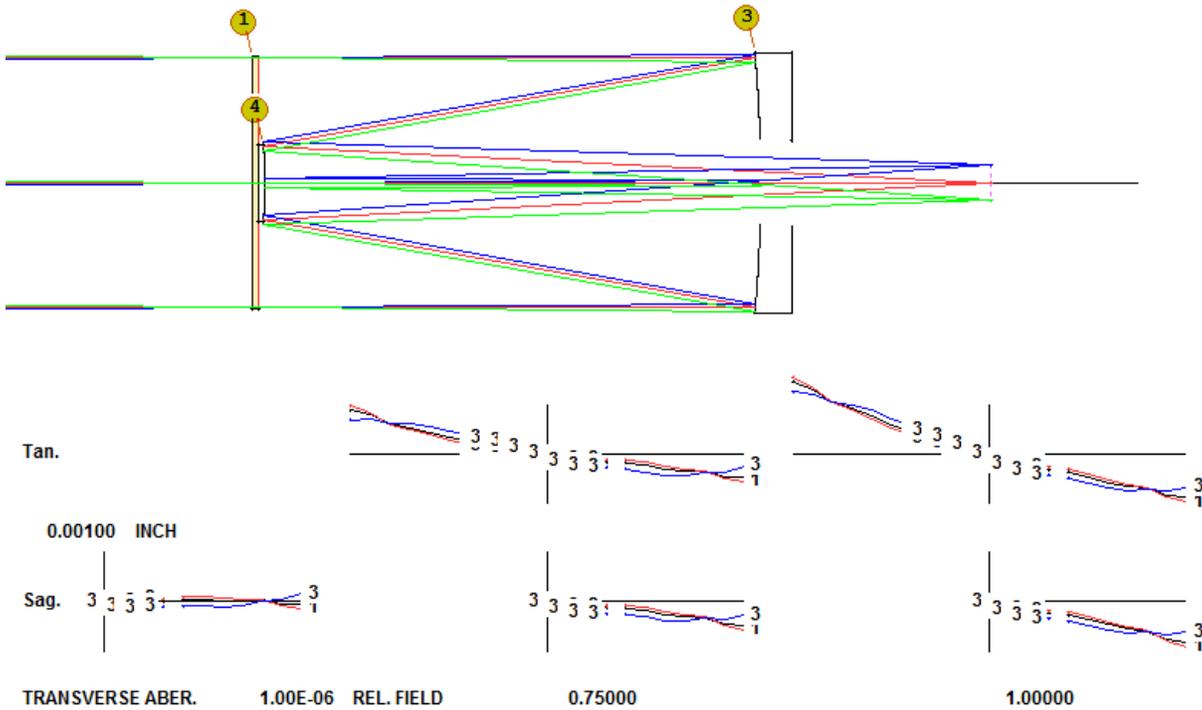


Let's discuss that elliptical aperture on surface 2. In the WS, select surface 2 and then click the button, , to open the Edit Aperture dialog. The option **User-entered elliptical aperture** is selected; click that button to display another dialog where you can change the numbers if you wish. Diagonal mirrors are usually edged with an elliptical shape, and this is where you can enter the data. (Or you can just edit the numbers in the WS edit pane, once you identify them.)

Schmidt-Cassegrain Telescope

```
RLE
ID CC SCHMIDT CASS ZERNIKE
FNAME 'SCT.RLE
WAVL .6562700 .5875600 .4861300
APS 1
GLOBAL
UNITS INCH
OBB 0.000000 0.40800 5.00000 0.00000 0.00000 0.00000 5.00000
MARGIN 0.050000
BEVEL 0.010000
0 AIR
1 CV 0.0000000000000000 TH 0.25000000
1 N1 1.51981155 N2 1.52248493 N3 1.52859442
1 GTB S 'K5
1 EFILE EX1 5.050000 5.050000 5.060000 0.000000
1 EFILE EX2 5.050000 5.050000 0.000000
2 CV 0.0000000000000000 TH 20.17115161 AIR
2 AIR
2 ZERNIKE 5.00000000 0.00000000 0.00000000
ZERNIKE 3 -0.00022795
ZERNIKE 8 0.00022117
ZERNIKE 15 -2.00317788E-07
ZERNIKE 24 -3.81789104E-08
ZERNIKE 35 -3.47468956E-07
ZERNIKE 36 3.76974435E-07
2 EFILE EX1 5.050000 5.050000 5.060000
3 CAI 1.68000000 0.00000000 0.00000000
3 RAD -56.8531404724216 TH -19.92114987 AIR
3 AIR
3 EFILE EX1 5.204230 5.204230 5.214230 0.000000
3 EFILE EX2 5.204230 5.204230 0.000000
3 EFILE MIRROR 1.250000
3 REFLECTOR
4 RAD -23.7669696838233 TH 29.18770982 AIR
4 CC -1.54408563
4 AIR
4 EFILE EX1 1.555450 1.555450 1.555450 0.000000
4 EFILE EX2 1.545450 1.545450 0.000000
4 EFILE MIRROR -0.243545
4 REFLECTOR
4 TH 29.18770982
4 YMT 0.00000000
BTH 0.01000000
5 CV 0.0000000000000000 TH 0.00000000 AIR
5 AIR
END
```

Note how the vignetted rays are identified on the fans plots in PAD. Switch 21 is honored there as well (and you can turn it off if you'd rather see the default display).



On the SPEC listing you see that surfaces 2 and 4 are aspheric, denoted by the "O" after the radius column

SYNOPTSYS AI>SPEC

ID CC SCHMIDT CASS ZERNIKE
LENS SPECIFICATIONS:

SYSTEM SPECIFICATIONS

OBJECT DISTANCE (TH0)	INFINITE	FOCAL LENGTH (FOCL)	98.1614
OBJECT HEIGHT (YPP0)	INFINITE	PARAXIAL FOCAL POINT	29.1777
MARG RAY HEIGHT (YMP1)	5.0000	IMAGE DISTANCE (BACK)	29.1877
MARG RAY ANGLE (UMP0)	0.0000	CELL LENGTH (TOTL)	0.5000
CHIEF RAY HEIGHT (YPP1)	0.0000	F/NUMBER (FNUM)	9.8161
CHIEF RAY ANGLE (UPP0)	0.4080	GAUSSIAN IMAGE HT (GIHT)	0.6992
ENTR PUPIL SEMI-APERTURE	5.0000	EXIT PUPIL SEMI-APERTURE	2.0218
ENTR PUPIL LOCATION	0.0000	EXIT PUPIL LOCATION	-10.5157

WAVL (uM) .6562700 .5875600 .4861300

WEIGHTS 1.000000 1.000000 1.000000

COLOR ORDER 2 1 3

UNITS

APERTURE STOP SURFACE (APS) 1 INCH

SEMI-APERTURE 5.00000

FOCAL MODE ON

MAGNIFICATION -9.81862E-11

GLOBAL OPTION ON

BTH OPTION ON, VALUE = 0.01000

GLASS INDEX FROM SCHOTT OR OHARA ADJUSTED FOR SYSTEM TEMPERATURE

SYSTEM TEMPERATURE = 20.00 DEGREES C

POLARIZATION AND COATINGS ARE IGNORED.

SURFACE DATA

SURF	RADIUS	THICKNESS	MEDIUM	INDEX	V-NUMBER
0	INFINITE	INFINITE	AIR		
1	INFINITE	0.25000	K5	1.52248	59.49 SCHOTT
2	INFINITE O	20.17115	AIR		

```

3      -56.85314      -19.92115      AIR      <-
4      -23.76697 O    29.18771S      AIR
IMG      INFINITE

```

KEY TO SYMBOLS

```

A SURFACE HAS TILTS AND DECENTERS      B TAG ON SURFACE
G SURFACE IS IN GLOBAL COORDINATES     L SURFACE IS IN LOCAL COORDINATES
O SPECIAL SURFACE TYPE                  P ITEM IS SUBJECT TO PICKUP
S ITEM IS SUBJECT TO SOLVE              M SURFACE HAS MELT INDEX DATA
T ITEM IS TARGET OF A PICKUP

```

SPECIAL SURFACE DATA

```

SURFACE NO. 2 -- ZERNIKE POLYNOMIAL
APER. SIZE OVER WHICH ZERNIKE COEFF. ARE ORTHOGONAL (AP) 5.000000
TERM      COEFFICIENT      ZERNIKE POLYNOMIAL
3         -0.000228        2*R**2-1
8         0.000221         6*R**4-6*R**2+1
15        -2.003178E-07     20*R**6-30*R**4+12*R**2-1
24        -3.817891E-08     70*R**8-140*R**6+90*R**4-20*R**2+1
35        -3.474690E-07     252*R10-630*R8+560*R6-210*R4+30*R2-1
36        3.769744E-07      924*R12-2772*R10+3150*R8-1680*R6+420*R4-42*R2+1

```

```

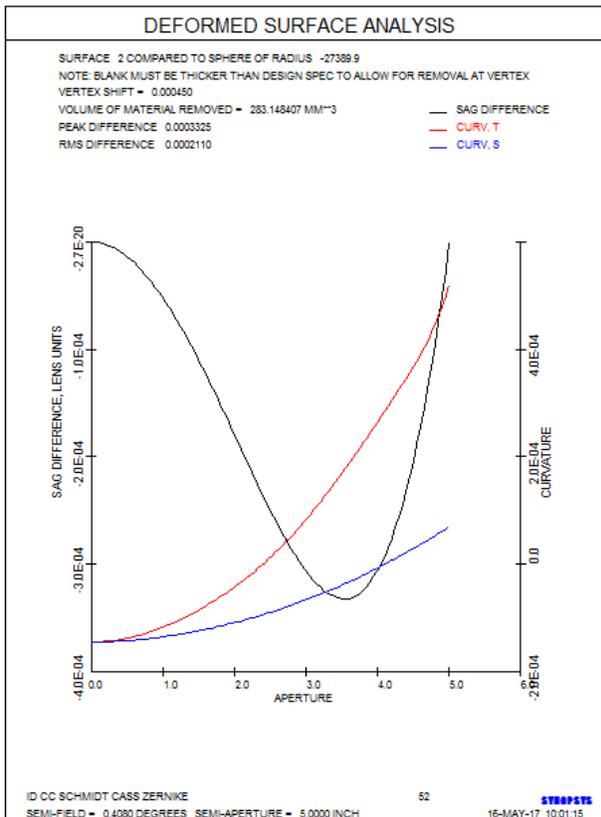
SURFACE NO. 4 -- CONIC SURFACE
CONIC CONSTANT (CC)      -1.544086
SEMI-MAJOR AXIS (b)      43.682407  SEMI-MINOR AXIS (a)  -32.221087

```

THIS LENS HAS NO TILTS OR DECENTERS
SYNOPSIS AI>

Surface 2 is defined as a Zernike polynomial aspheric. Let's see what that surface looks like. Type

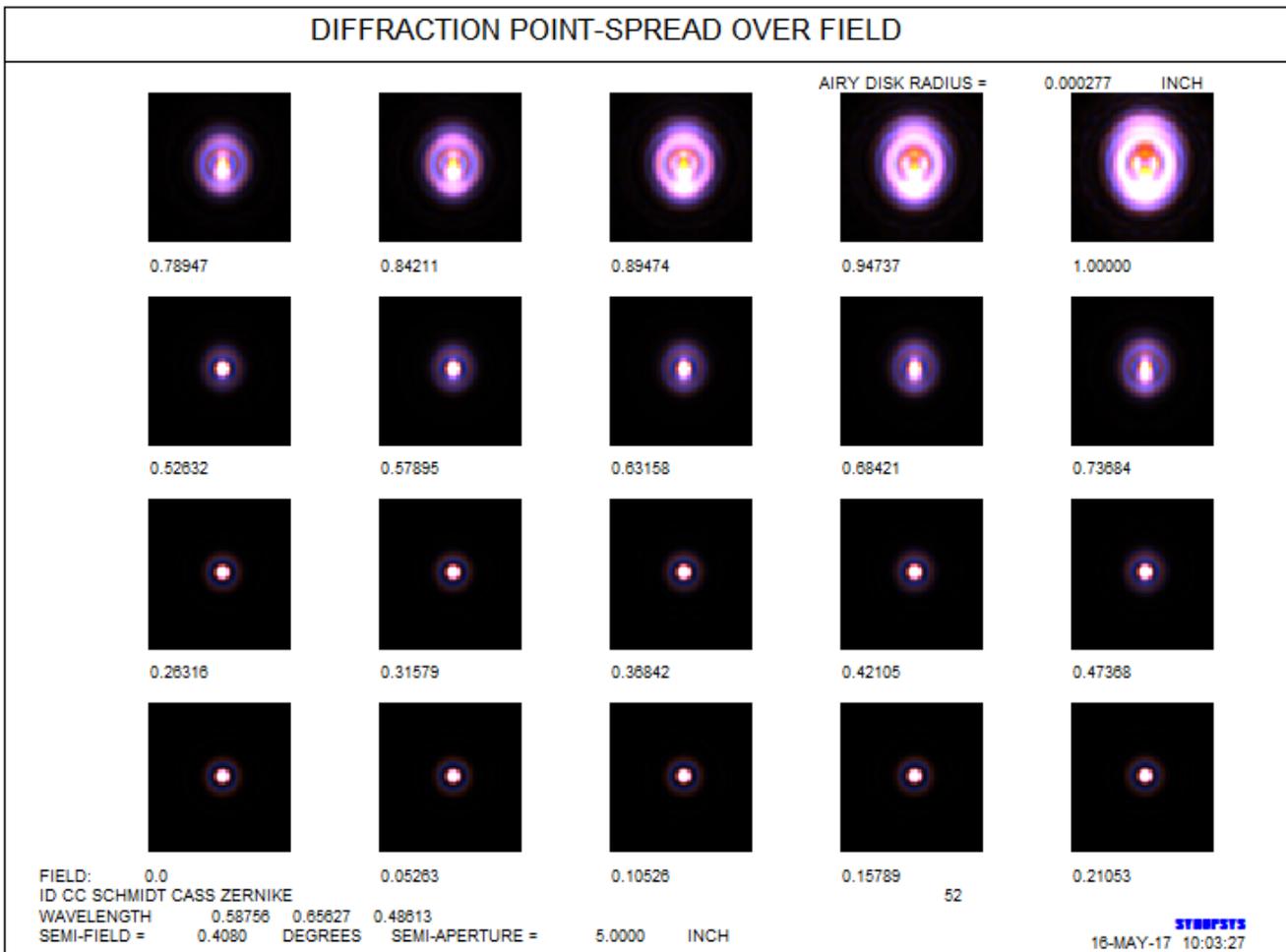
ADEF 2 PLOT



The black curve in the above picture shows how the surface departs from the closest-fitting sphere, which in this case is very close to flat.

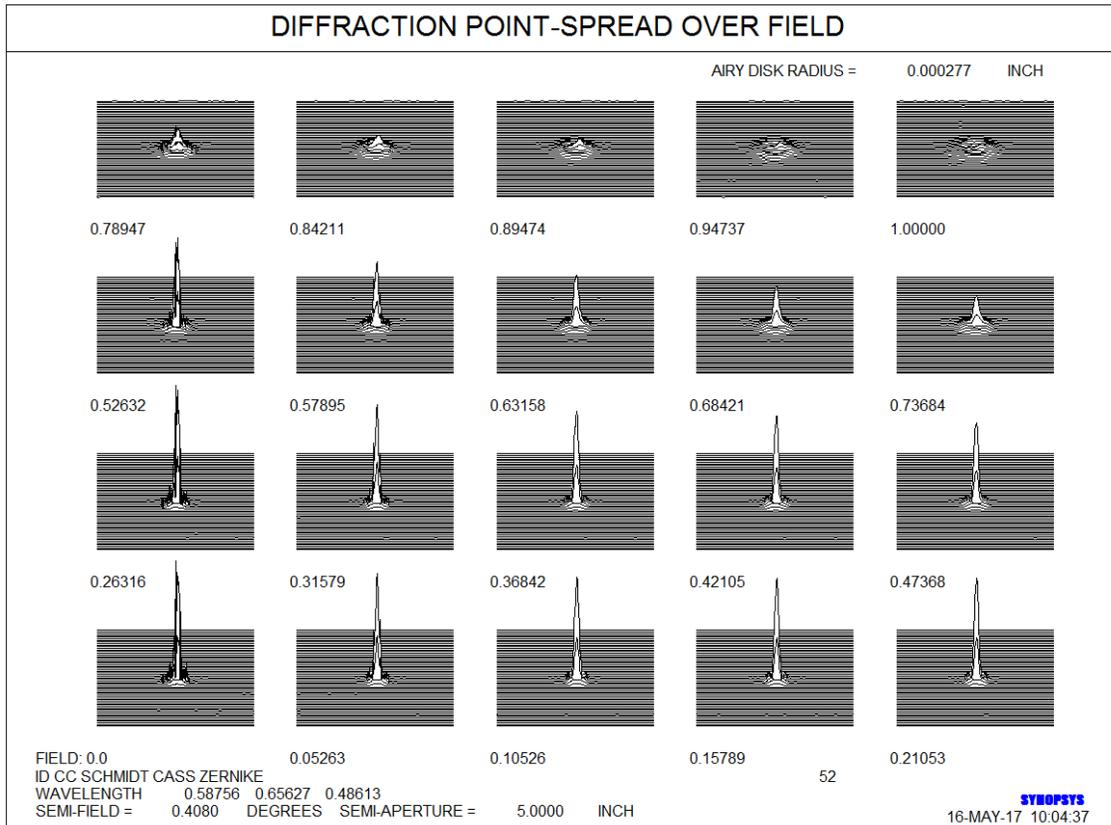
The ray fans curves in PAD show the system free from coma and spherical aberration, although there is a tiny bit of sphero-chromatism. (That is the term for spherical aberration whose magnitude changes with color.) The striking thing is the strong field curvature, indicated by the nearly parallel S- and T-fan curves. A young viewer with a good eyepiece would therefore see a sharp image all over the field, since young eyes can accommodate for the focus shift. Without refocusing, on the other hand, an older viewer would be faced with about 1.5 waves of defocus. Let's see what that would look like over the the field.

Here, it's probably easiest to start at the menu tree and go down to MDI (Menu, Diffraction Image), where you get many choices. Select MPF, near the bottom (or just type **MPF** in the CW). Select **Show visual appearance** and click **Execute**:



The image at the lower left is the on-axis image, while the upper right is the edge of the field. That's not too sharp. Let's examine it in a different format. Back in MPF, select the option to **Show as surface**, and change the Height from the default 1 to 0.

Indeed, the image at the edge of the field is pretty smeared out.



You can edit the Zernike terms most easily by just changing the value in the WS, but there is also a dialog that lists them by polynomial, which you can reach from the WS by clicking the button, , and following the trail as you did the aperture dialog, above. You arrive at this dialog, where you can change things if you want:

Edit Lens Data

Coefficient	Function
0	1 RCOS(A)
0	2 RSIN(A)
-0.00022795	3 2R**2-1
0	4 R**2COS(2A)
0	5 R**2SIN(2A)
0	6 (3R**2-2)RCOS(A)
0	7 (3R**2-2)RSIN(A)
0.00022117	8 6R**4-6R**2+1
0	9 R**3COS(3A)
0	10 R**3SIN(3A)
0	11 (4R**2-3)R**2COS(2A)
0	12 (4R**2-3)R**2SIN(2A)
0	13 (10R**4-12R**2+3)RCOS(A)
0	14 (10R**4-12R**2+3)RSIN(A)
-2.00317788e-007	15 20R**6-30R**4+12R**2-1

Unit aperture: X-offset: Y-offset:

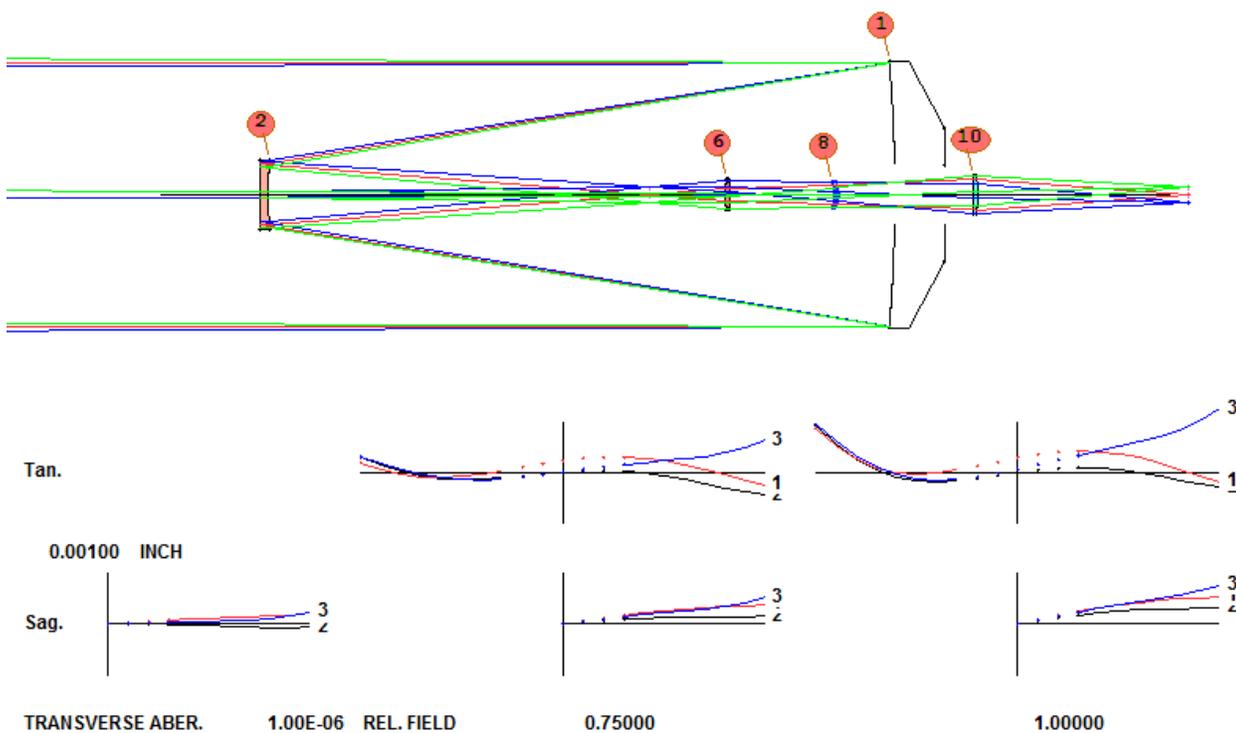
The Relay Telescope

This example is a relay telescope that the author built in his basement some years ago. An early version was described in *Sky & Telescope* in 1977, but this one has an extra relay lens and is better corrected. It comes bundled with the program as file 4.RLE, and you can open it with the command

FETCH 4 .

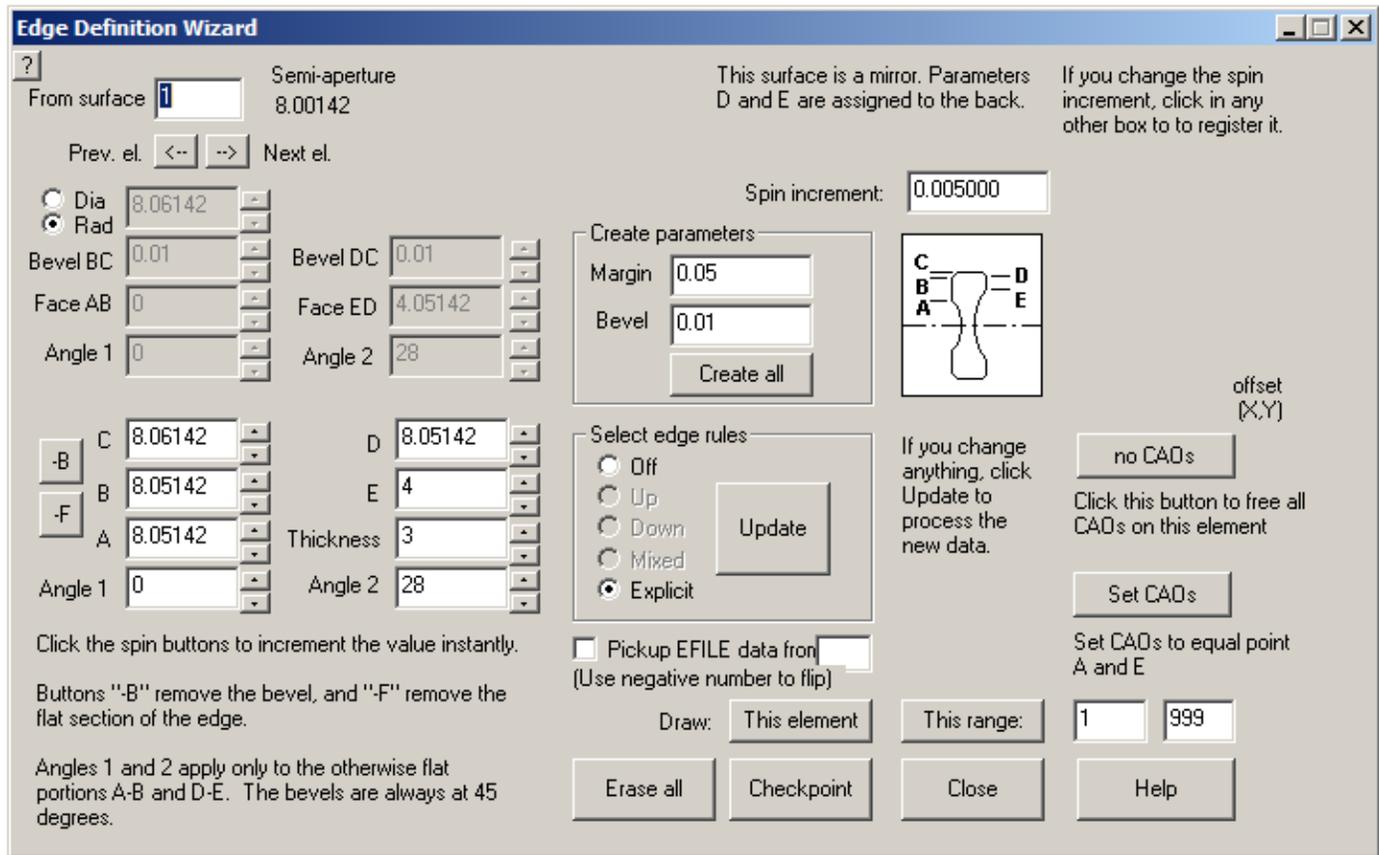
You can also open **MWL** (Menu, Window, Lens) to see all of the lens files in the current user directory, with a preview pane for any file you click on.

The version shown here has a 16-inch diameter mirror, and all surfaces are spherical, making it easy to build, compared to an aspheric design.



By now you should be able to enter, modify, and evaluate designs like this without much coaching. The interesting point of this design is the use of a Mangin mirror, from surfaces 2 to 4. Surface 3 is a reflector, and surface 4 is coincident with surface 2. With this element, both spherical aberration and secondary color can be well corrected. This telescope has given me and my friends many years of excellent viewing of the heavens. When the file is opened, type **LEO** in the CW to examine the input file.

The shape of the primary mirror, which in my case was ground to a cone shape on the back, was entered with **EFILE** data, which are used to describe edges of elements. In PAD, click the button,  to open the Edge Wizard (or type **MEW**, Menu, Edge Wizard), and select surface 1, if it was not selected in WS.



This dialog is where you will define up to five points on lenses and mirrors, as identified by the small diagram. In the case of a reflective surface, two of the edit boxes are assigned to the mirror thickness (here 3 inches) and cone angle on the back (here 28 degrees). Point E in this case marks the start of the cone, 4 inches from the axis. Click the **Next el.** button, and the program jumps to the first side of the next lens. Jump around, and see how the parameters A through E define the shape of the lens edges. Then click the button, , to read about all the things you can do with the edge definition, or EFILE data.

In this lesson we have covered only a few of the many powerful features available in SYNOPSIS™. Feel free to poke around in the other dialogs and see for yourself the many tools you now have available.