Optical Design Tutorials
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General Instructions

Optical System Specifications

In every design exercise, certain optical system specifications re required in order to know what is to be designed. Each tutorial exercise will begin with such a specification.

Graphics Displays

No graphical output will be included in this tutorial because it makes the document unnecessarily bulky. Any time a command generates graphical output, that output is drawn to a new screen. Pressing any key clears that screen. The screen may be re-drawn by issuing the **DRAW** command or the screen may be printed by issuing the **GRAOUT** command which sends the graphics to the current default Windows printer.

Using the Tutorials

I am assuming that those who are running these tutorials know something about optical design and analysis and are running the tutorials in order to overcome NEW USER ANGST which, trust me on this one, we all have from time to time. The tutorials will start simple and bet progressively more complex, though compared to some areas of scientific computing, what you will be doing here is relatively simple and straight forward. Please email any and all questions and complaints to the email address above.

Tutorial #1

Designing an Newtonian Telescope

System specifications:

Telescope aperture diameter = 6.0 inches. Telescope focal ratio = f/8. Telescope tube outside diameter = 7.0 inches. Distance outside the tube at which the infinite conjugate focus is to be placed = 2.0 inches.

We start by starting the program in the usual way, double clicking either on the program icon or its shortcut on the desk top. At the command prompt, we now enter the telescope prescription. All input commands are in **BOLD CAPS**. In tutorial #1, bracketed descriptors describe all commands. In following tutorials, only newly introduced commands will have bracketed descriptors and only in their first usage.

LENS {starts lens input}
LI,MY 6", F/8 NEWTORNIAN TELESCOPE {names the lens}
UNITS IN {sets the units to inches - the default}
EPD 6 {sets the entrance pupil diameter to 6.0 inches}
SCY FANG .25 {sets the half angle of the field to 1/4 degree}
TH 1E20 {sets the distance from the object to the first surface}
AIR {defines the material to be air - refractive index = 1.0 and stops current surface data input}
AIR {inserts a dummy surface}
TH 48 {sets the distance to the next surface to 48 inches}
AIR {sets the material to air and stops current surface data input}
RD -96 {sets the radius of curvature of the mirror to 96.0 inches}
CC -1 {sets the mirror conic constant to -1 - a parabola}
TH -48 {sets the distance to the next surface to 48 inches}
ASTOP {sets primary mirror to be the aperture stop}
REFS {sets the primary mirror to be the real ray reference surface}

CLAP 3.0 {sets the clear aperture radius to be 3.0 inches on the primary mirror}
REFL {sets the surface to be a mirror and stops current surface input}
AIR {inputs a dummy surface}
AIR {inputs another dummy surface}
END {stops all lens input and returns you to the CMD program level}

I admit, a bit cryptic but its much faster than a spread sheet after you do a few designs. The bracketed comments tell you what each command did.

Remember, a Newtonian telescope has a parabolic primary mirror and the radius of curvature is always twice the focal length. Also, every other reflection reverses the beam path with respect to the local Z-axis so that is why the distance from the mirror is specified as a negative distance.

Let's take a look. By typing: **VIE** {view the lens} and pressing the return key (you always need to press the return key after all commands) you will get a quick YZ-plane picture of your telescope. Pressing any key will close the drawing window. Now let's add the folding flat. We want the final focus to lie 2 inches outside of the 7.0 inch diameter tube so we need to place a fold mirror in the beam 2.0 + 7.0/2 or 5.5 inches in front of the final focus. Before we make the changes, list out the lens prescription with the **RTG ALL** {radius-thickness-glass all surface listing}. The output looks like this:

```
BASIC LENS DATA (RADIUS MODE)

SURF  RADIUS        THICKNESS         MATERIAL          INDEX        V-NUM
  0    0.00000      0.100000E+21        AIR
  1    0.00000       0.00000            AIR
  2    0.00000       48.0000            AIR
  3*  -96.0000      -48.0000            REFL
  3*Conic,REFS,STOP
  4    0.00000       0.00000            AIR
  5    0.00000       0.00000            LAST SURFACE
```

Now to change the thickness of surface #3 to 42.5 inches and make surface #4 a fold mirror and have the total distance from the mirror to the focal plane to remain at 48.0 inches we enter the following update lens commands:

U L {go into update lens mode}
CHG 3 {change surface #3}
TH -42.5 {set surface #3 thickness to -42.5 inches}
CHG 4 {change surface #4}
TH 5.5 {set surface #4 thickness to 5.5 inches}
REFL {set surface #4 to be a mirror}
TILT BEN -45 {define surface #4 as a fold mirror with TILT BEN}
END {return to CMD program level}

Now if you enter the **VIE** {yz-plane view} command again you will see the telescope with its fold mirror.

Next you will want to set the clear aperture on the fold mirror so that it is large enough to pass all the light coming from the primary mirror from all points in the full +/- 0.25 degree field of view. Do this buy typing:

U L {go into update lens mode}
CHG 4 {change surface #4}
CLAP ELIP 1,2 {assign an elliptical clear aperture with place holder numeric values 1 and 2}
END {return to the CMD program level}
SETCLAP {automatically adjust clear aperture data on all surfaces based on automatic ray traces in the yz and xz-planes} NOTE: For manufacturing considerations only, add an additional 0.40 to 0.80 inch on the radius of all automatically assigned clear apertures before having the parts fabricated.

The resultant clear aperture on surface #4 and the user-assigned clear aperture on surface #3 can be listed by issuing the **CAOB ALL** {list all clear aperture data} command:

```
CAOB ALL      {list all clear aperture data}

CLEAR APERTURES AND OBSCURATIONS

SURF     TYPE    Y-SEMI.     X-SEMI.     Y-DEC       X-DEC  CORNER-RADIUS TILT(DEG)
                (RADIUS)   (N-POLY)
                           (RAD-FLT)                           (DELTA-Z)
  3      CIRC    3.00       3.00
  4      ELIP   0.752      0.530     -0.438E-01
```

The off-set in the Y-direction comes from the geometry of elliptical fold mirrors and is correct.

Now, how good is the design? By definition, performance is perfect (no geometrical aberration and diffraction limited) on-axis. This is true for all parabolic mirrors on-axis. At the edge of the field of view, at the control wavelength which by default is = 0.58756 microns, the optical path errors can be listed by issuing the following three commands.

FOB 1 {define the field of view position to be + 0.25 degree in the Y-direction}
YFAN OPD -1 1 1 11 {do an 11 ray OPD fan of rays in the yz-plane}

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS A  "YFAN"
FRACTIONAL FAN OFFSET =    0.00000     (RELATIVE TO FULL APERTURE)
OPD REFERENCE WAVLENGTH =   0.587560     MICRONS

 REL AP HT     OPD (LENS UNITS)     OPD (WAVE UNITS)
  -1.0000      0.1454911383E-04       0.62895
  -0.8000      0.7680481083E-05       0.33202
  -0.6000      0.3401836999E-05       0.14706
  -0.4000      0.1103375268E-05       0.47699E-01
  -0.2000      0.1736397266E-06       0.75064E-02
   0.0000       0.000000000            0.0000
   0.2000     -0.3087070866E-07      -0.13345E-02
   0.4000     -0.5325166512E-06      -0.23020E-01
   0.6000     -0.2118220316E-05      -0.91570E-01
   0.8000     -0.5400523676E-05      -0.23346
   1.0000     -0.1099075095E-04      -0.47513
```

XFAN OPD -1 1 1 11 {do an 11 ray OPD fan of rays in the XZ-plane}

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS AN "XFAN"
FRACTIONAL FAN OFFSET =    0.00000     (RELATIVE TO FULL APERTURE)
OPD REFERENCE WAVLENGTH =   0.587560     MICRONS

 REL AP HT     OPD (LENS UNITS)     OPD (WAVE UNITS)
  -1.0000     -0.4357403327E-09      -0.18837E-04
  -0.8000     -0.1784812298E-09      -0.77157E-05
  -0.6000     -0.5647393664E-10      -0.24413E-05
  -0.4000     -0.1116262638E-10      -0.48256E-06
  -0.2000       0.000000000            0.0000
   0.0000       0.000000000            0.0000
   0.2000       0.000000000            0.0000
   0.4000     -0.1116262638E-10      -0.48256E-06
   0.6000     -0.5647393664E-10      -0.24413E-05
   0.8000     -0.1784812298E-09      -0.77157E-05
   1.0000     -0.4357403327E-09      -0.18837E-04
```

The optical OPD error is seen to be over one wave peak to valley at the edge of the field of view.

Now save the design in lens library position 100 by issuing a **LIB PUT 100** command. Later you can list the contents of the lens library by typing **LIB P** and the lens can be retrieved from the library with a **LIB GET 100** command.

Finally, let's document the design. By typing **OUT LP**, the output device for the program will be changed from the screen to the file PRINTER.TXT. Now issue the following commands:

LEPRT {outputs the prescription in a human readable format}
LENO {outputs the design in a format which can be read back into the program at a future date}
OUT TP {resets the screen as the output device}
PRINT {prints the PRINTER.TXT file to the Windows print manager}

Now lets get some graphics output. Issue the following commands:

VIE .1 {generates a YZ-plane picture of the design at 1/10 scale}
GRAOUT {sends the plot to the Windows Print Manager}
VIE ORTHO .1 {generates an orthographic picture of the design at 1/10 scale}
GRAOUT {sends the plot to the Windows Print Manager}
FANS XYOPD 1 {generates the XY OPD fans on-axis, 0.7 and 1.0 fractional FOV with a 1.0 wave scale bar}
GRAOUT {sends the plot to the Windows Print Manager}

Finally, issue the following commands:

FOB
FANS {generates x-components of an x-fan and the y-components of a y-fan transverse aberration plot}

We see from this plot that the dominant residual aberration in the system is COMA (reflected by the symmetric transverse ray aberration plots in the y-fan.).

That's all there is to doing your first design. In the next exercise, we will design a classical Cassegrain telescope.

Extra Analysis

The following things may be done to enhance the analysis of the telescope in tutorial #1 or any design in later tutorials.

DISPLAY FIRST-ORDER, YZ-PLANE PARAXIAL RAY TRACE DATA
Command: **PXTY ALL**

```
PARAXIAL RAYTRACE DATA (YZ-PLANE) - (CFG # 1)
(PUY AND PUCY) MEASURED WITH RESPECT TO THE Z-AXIS

SURF       PY             PUY             PCY            PUCY
  0   0.00000       0.300000E-19  -0.436335E+18   0.436335E-02
  1   3.00000       0.300000E-19  -0.209441       0.436335E-02
  2   3.00000       0.300000E-19  -0.209441       0.436335E-02
  3   3.00000       0.625000E-01  -0.555112E-16  -0.436335E-02
  4  0.343750      -0.625000E-01   0.185442       0.436335E-02
  5   0.00000      -0.625000E-01   0.209441       0.436335E-02
```

DISPLAY THIRD-ORDER, YZ-PLANE ABERRATION DATA
Command: **MAB3 ALL**

```
(Y-Z), PLANE THIRD ORDER
```

```
ABERRATION CONTRIBUTIONS - (CFG # 1)
TRANSVERSE - WITH FINAL SURFACE CONVERSION

SURF     SA3           CMA3          AST3          DIS3          PTZ3
  0    0.0000        0.0000        0.0000        0.0000        0.0000
  1    0.0000        0.0000        0.0000        0.0000        0.0000
  2    0.0000        0.0000        0.0000        0.0000        0.0000
  3    0.0000       0.61360E-03  -0.28558E-04    0.0000       0.28558E-04
  4    0.0000        0.0000        0.0000        0.0000        0.0000
  5    0.0000        0.0000        0.0000        0.0000        0.0000
SYSTEM TOTALS ARE:
       0.0000       0.61360E-03  -0.28558E-04    0.0000       0.28558E-04
```

Tutorial #2

Designing Cassegrain Telescopes

System specifications:

Telescope aperture diameter = 12.0 inches. Primary mirror focal ratio = f/3. Final telescope focal ratio = F/18. Primary mirror thickness 3.0 inches. Secondary mirror thickness 0.5 inch. Field of view = +/- 0.25 degrees. The design will be a classical Cassegrain design comprising a parabolic primary mirror and a hyperbolic secondary mirror.

Issue the following commands to set up the Cassegrain telescope in a "pre-optimization" configuration. The design will be optimized by automatically adjusting the conic constant of the secondary mirror until the third order spherical aberration has been driven to 0.0.

LENS
LI MY 12 INCH, F/18 CASSEGRAIN TELESCOPE.
UNITS IN
EPD 12.0
SCY FANG 0.25
TH 1.0E20
AIR
AIR
TH 36
AIR
RD –72 {sets primary mirror radius of curvature to -72 inches}
CC –1 {sets primary mirror to a parabolic profile}
PY , 1 {paraxial marginal ray height solve-adjusts the airspace following the primary mirror so than the next surface is located where the paraxial marginal ray has a height of 1.0 inch. This is necessary for the 6:1 focal length "magnification" in going from the F/3 primary to the final focal ratio of F/18.)
ASTOP
REFS
THM 3 {set mirror thickness to 3.0 inches}
CLAP 6
REFL
PUY -.0277777777 {paraxial marginal ray angle solve-adjusts the secondary mirror curvature so that the slope of the marginal paraxial ray leaving the secondary mirror has a 1/36 slope (required for the final F/18 focal ratio)}
PY {paraxial marginal ray height solve-adjusts the airspace after the secondary mirror so that the next surface will always be at the paraxial focal position}
THM 0.5 {sets the thickness of the secondary mirror to 0.5 inch}
REFL
AIR
AIR

END

Now we are going to let the conic constant on the secondary mirror vary during optimization. To do this type:

VARI
CC 4
END

Now we will set up the optimization figure of merit so as to drive the third order spherical aberration to zero. To do this type:

MERIT
SA3
END

Now run one cycle of direct optimization by typing:

IT D {IT D is a direct rather than damped least squares type of optimization and is useful when there is only one operand and one variable. In this case it usually converges in one cycle}

The result is:

```
 CALCULATING DERIVATIVES, PLEASE WAIT...
 CALCULATING A SOLUTION VECTOR, PLEASE WAIT...
    NEW FMT =   0.0.176694601778536E-21 (or some other very small #)
    OLD FMT =   0.558395862792566E-03
FMT(CHANGE) =  -0.558395862792566E-03
```

Checking that the spherical aberration on-axis is now zero is done by issuing the following two commands from the last tutorial:

FOB
YFAN OPD –1 1 1 11

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS A  "YFAN"
FRACTIONAL FAN OFFSET =    0.00000     (RELATIVE TO FULL APERTURE)
OPD REFERENCE WAVLENGTH =   0.587560     MICRONS

 REL AP HT     OPD (LENS UNITS)     OPD (WAVE UNITS)
  -1.0000       0.000000000           0.0000
  -0.8000       0.000000000           0.0000
  -0.6000       0.000000000           0.0000
  -0.4000       0.000000000           0.0000
  -0.2000       0.000000000           0.0000
   0.0000       0.000000000           0.0000
   0.2000       0.000000000           0.0000
   0.4000       0.000000000           0.0000
   0.6000       0.000000000           0.0000
   0.8000       0.000000000           0.0000
   1.0000       0.000000000           0.0000
```

The conic constant on the secondary mirror was automatically adjusted to make the third order (and in fact all spherical aberration) go to zero.

Now list the conic constants in the design by typing:

ASPH ALL {lists all conic and aspherics to 20th order}

```
CONIC AND 4th THROUGH 10th ORDER ASPHERIC DATA
(+) - DESIGNATES A PLANO SURFACE WITH A 2ND ORDER ASPHERIC
TERM IN THE SECOND COLUMN INSTEAD OF A CONIC CONSTANT

SURF     CC
  3  -1.00000
  4  -1.96000
NO 12th through 20th ORDER ASPHERIC DATA
```

Now let us examine the optical performance at the edge of the field of view. We already know that there are no aberrations on-axis. At the edge of the field of view, the OPDs are:

FOB 1
YFAN OPD –1,1,1,11

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS A  "YFAN"
FRACTIONAL FAN OFFSET =    0.00000     (RELATIVE TO FULL APERTURE)
OPD REFERENCE WAVLENGTH =   0.587560     MICRONS

 REL AP HT     OPD (LENS UNITS)     OPD (WAVE UNITS)
  -1.0000      0.3629234148E-04        1.5689
  -0.8000      0.2259726686E-04       0.97687
  -0.6000      0.1235529565E-04       0.53411
  -0.4000      0.5332558146E-05       0.23052
  -0.2000      0.1293317517E-05       0.55910E-01
   0.0000       0.000000000            0.0000
   0.2000      0.1213227002E-05       0.52447E-01
   0.4000      0.4691847678E-05       0.20283
   0.6000      0.1019297306E-04       0.44064
   0.8000      0.1747201145E-04       0.75531
   1.0000      0.2628270481E-04        1.1362
```

XFAN OPD –1,1,1,11

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS AN "XFAN"
FRACTIONAL FAN OFFSET =    0.00000     (RELATIVE TO FULL APERTURE)
OPD REFERENCE WAVLENGTH =   0.587560     MICRONS

 REL AP HT     OPD (LENS UNITS)     OPD (WAVE UNITS)
  -1.0000      0.2311390936E-04       0.99921
  -0.8000      0.1479826035E-04       0.63972
  -0.6000      0.8326366178E-05       0.35995
  -0.4000      0.3701351680E-05       0.16001
  -0.2000      0.9254496334E-06       0.40007E-01
   0.0000       0.000000000            0.0000
   0.2000      0.9254496334E-06       0.40007E-01
   0.4000      0.3701351680E-05       0.16001
   0.6000      0.8326366192E-05       0.35995
   0.8000      0.1479826035E-04       0.63972
   1.0000      0.2311390936E-04       0.99921
```

As can be seen, the telescope is not diffraction limited at the edge of the field of view. If we compare a transverse ray aberration plot of this system via a simple **FOB , 1** and a **FANS** command with the **FOB, 1** and **FANS** command run on the previous design in tutorial #1, we see that the dominant residual aberration in the F/8 Newtonian was COMA whereas the dominant residual aberration in the F/18 Cassegrain is field curvature.

Now save the design in library file # 101 with a **LIB PUT 101** command

Tutorial #3

Two Mirror Afocal Beam Compressor

System specifications:

Input beam diameter = 12.0 inches, output beam diameter 4.0 inches. Primary/secondary mirror focal ratios, F/6. Primary mirror aperture 12.0 inches. Aperture stop on primary mirror. Primary mirror thickness 3.0 inches. Secondary mirror thickness 0.5 inch. Field of view = +/- 0.1 degrees. The design form will be con-focal concave parabolic mirrors. Wavelength will be 10.6 microns.

Issue the following commands to set up the telescope:

LENS
UNITS IN
WV 10.6 0 0 0 0 {change wavelengths to 10.6 microns with wavelengths 2 through 5 set to zero}
EPD 12.0
SCY FANG 0.1
TH 1E20
AIR
AIR
TH 72
AIR
RD –144
CC –1
TH -72
CLAP 6
ASTOP
REFS
REFL
TH –18
AIR
RD 36
TH 18
CLAP 1.5
CC –1
REFL
AIR
AIR
END
MODE AFOCAL {sets the evaluation mode of the program to AFOCAL}
VIEVIG OFF {turns off the automatic vignetting calculation in VIE}
SETCLAP {adjusts the clear aperture on the second parabola to ensure no vignetting of the off-axis beams.

Issuing a **VIE** command will display the system.

The on-axis performance is again perfect by the nature of the con-focal parabolas. At the edge of the field of view the performance is still diffraction limited. This is partially due to the small field of view and partially due to the long wavelength (10.6 microns).

FOB 1;YFAN OPD –1 1 1 11 {the semicolon can be used to string up to 20 commands together on one command line)

```
OPTICAL PATH DIFFERENCE TABLE : UNITS = INCHES
RAY FAN TRACED IS A  "YFAN"
FRACTIONAL FAN OFFSET =    0.00000      (RELATIVE TO FULL APERTURE)
```

```
OPD REFERENCE WAVLENGTH =    10.6000     MICRONS

 REL AP HT     OPD (LENS UNITS)      OPD (WAVE UNITS)
  -1.0000     -0.1904198531E-05      -0.45629E-02
  -0.8000     -0.1218642798E-05      -0.29201E-02
  -0.6000     -0.6854616802E-06      -0.16425E-02
  -0.4000     -0.3046385722E-06      -0.72998E-03
  -0.2000     -0.7615687173E-07      -0.18249E-03
   0.0000       0.000000000            0.0000
   0.2000     -0.7615133100E-07      -0.18248E-03
   0.4000     -0.3045942518E-06      -0.72988E-03
   0.6000     -0.6853121553E-06      -0.16422E-02
   0.8000     -0.1218288409E-05      -0.29193E-02
   1.0000     -0.1903506328E-05      -0.45612E-02
```

Issuing the **FANS XYOPD 0.25** will display the optical path errors on-axis, at 0.7 for the full field of view and at full field of view. The scale bar will be 0.25 waves @ 10.6 microns.

Now save this prescription in library location 102 by typing **LIB PUT 102**. A lens is retrieved from the library using the **LIB GET #** command where # may be any value between 1 and 999. The lens library may be viewed using the **LIB P** command and a partial listing from library location "i" to "j" may be produced using the command **LIB P i j**