Introduction to CODE V (with basic optics)

2012. 4

WikiOptics

YIM BOOBIN

YIM, BOOBIN

WikiOptics

Concerns
- Laser pico-projector
- HUD/HMD
- Optical pickup lens
- Interferometer
- Education

Career
- **WikiOptics** (2012~)
  - Optics engineering (Pico-projector etc.)
- **LG** Electronics (2004~2012)
  - SMB(BD/HD DVD/DVD/CD) PU
  - DVD Writer PU/BD-P PU
- **SAMSUNG** Electro-mechanics (2002~2004)
  - DVD-ROM/P PU
  - Lens for PU (Diffractive lens)
- **DAEWOO** Electronics(1995~2002)
  - Car CD/Audio CD/DVD-P PU

Education
- POSTECH, physics (Master, 1996)
  - A Study of Simultaneous Measurement of In-plane and Out-of-plane Displacement Using Holographic Interferometry
- Chung-ang Univ. (CAU), physics (1994)

- Korea National Open Univ., Japanese study (2010)
- Korea National Open Univ., English literature(2002)

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(2nd Day)

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References

- CODE V Reference Manual

- CODE V Seminar Notes
  - Introduction to CODE V, Spring 2001
  - Advanced Topics in CODE V , Spring 2001
  - Methods for Optical Design and Analysis, March 1999
  - Materials on the ORA website

- Eugene Hecht, ***Optics (2nd Edition)***, Addison Wesley(1989)

- W. J. Smith, ***Modern Optical Engineering***, McGraw-Hill(1990)

- J. C. Wyant and K. Creath, ***Chapter 1. Basic Wavefront Aberration Theory for Optical Metrology,*** APPLIED OPTICS AND OPTICAL ENGINEERING, VOL. XI, Academic Press, Inc.(1992)

- J. C Wyant, ***Zernike Polynomials for the Web***, http://www.optics.arizona.edu/jcwyant/

- Military Standardization handbook OPTICAL DESIGN MIL-HDBK-141 (1962)

1^{st} day

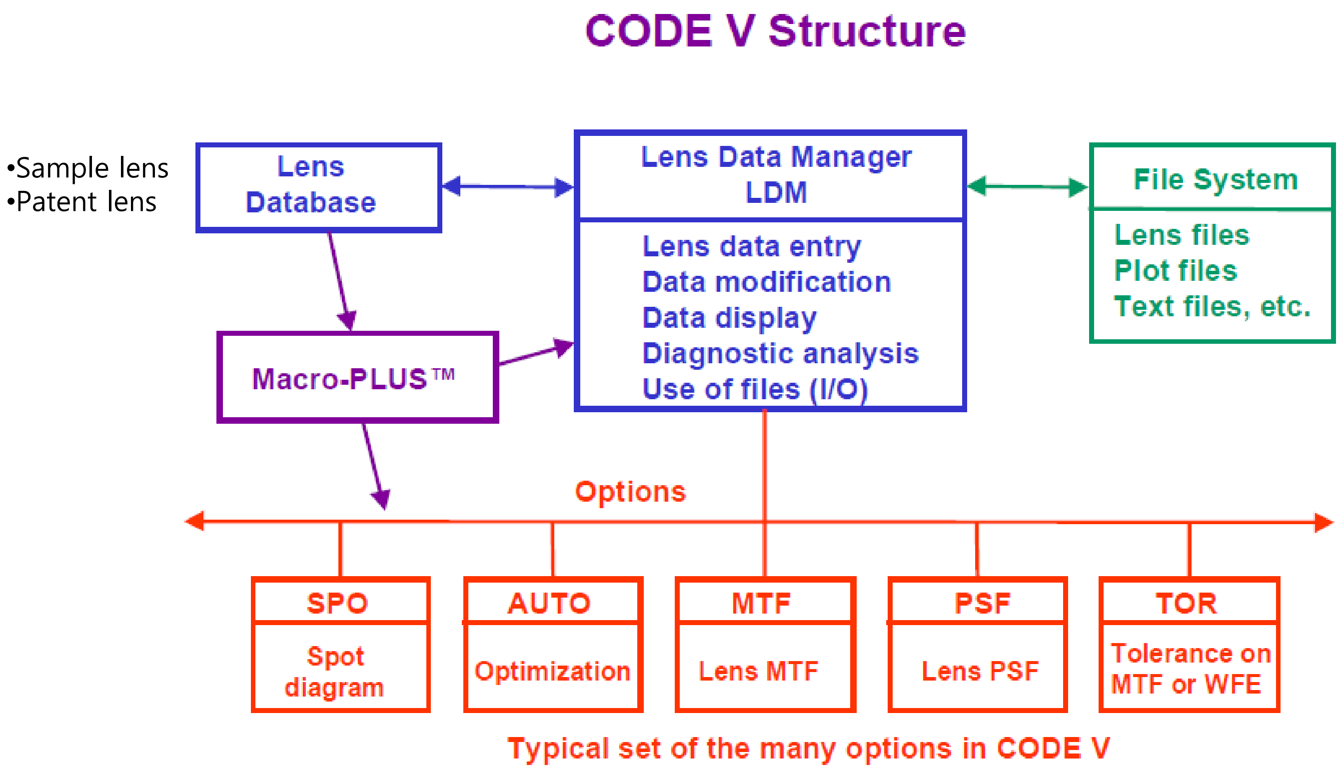
Section 1

Command mode

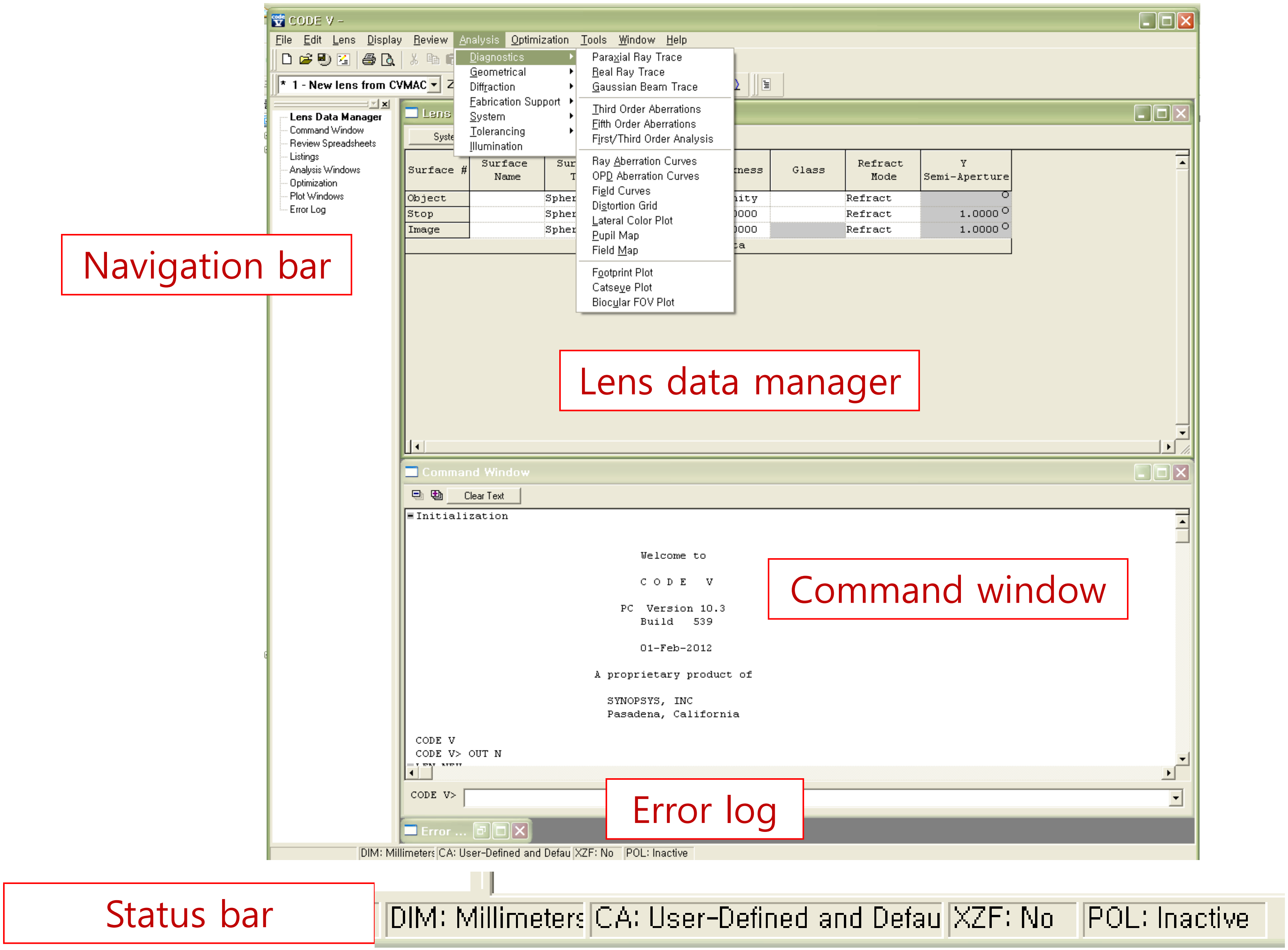
The structure of CODE V

- The Lens Data Manager(LDM) is where you manage the lens database
  - You can use both GUI and Command mode
  - In this lecture, I'll use mainly the Command mode

- CODE V's options are sophisticated, special purpose "report generators"



The structure of CODE V



Command mode

- Command mode is CODE V's native language.

- Experts and frequent users of CODE V often use command mode
  - Command mode is fast, powerful, and flexible
  - Allows stacking of commands on a single line (separated by ;)
  - Allows use of expressions in place of numbers

- Command mode requires more memorization
  - **Must know frequently used commands**
  - Proper syntax must be used

Command mode

- CODE V>
  - This prompt indicates you are in the LDM
- XYZ>
  - This prompt indicates you are in the XYZ option
- In options
  - **GO** command executes the option
  - **CAN**(CEL) commands you out of the option and back to the LDM
- Syntax Help
  - The proper syntax for a command can be seen by preceding the command with a backslash ****
  - CODE V> \ sur (or sur\)

    Syntax: SUR Sk|Si..j [F] [Zk]
  - **HEL [command [INDX]]**

Command structure

- **Command** **Qualifiers** **Data Items**

  1 to 3 chars none or more none or more

  - In general, qualifiers can be entered in any order(especially index qualifiers)
  - Data items usually have an order associated with them
  - Parts of commands are separated by white space(one or more blanks)

- Commands are case insensitive(except text strings)

Index Qualifiers

- Used to limit the command to a specific surface, field, wavelength, zoom position, etc.

- Are indicated by an appropriate letter(**S**, **F**, **W**, **Z**, etc.) followed by the surface number, field number, etc.
  - **S7**, **W3**, **Z2**, etc.

- Index qualifiers can include a range, indicated by ..
  - **S4..7**, **F1..3**

- Some special letters can be used in place of the numbers
  - **O = object, S = stop, I=image**
  - **L** can be used for last
  - **A** can be used for all(SA=S0..I, FA=F1..L)

- Addition and subtraction of index numbers can be used
  - **SI-1**, **SS+2, FL-2**, etc.

Data items

- Data items usually have an order associated with them

- For specification data, the data often both define and number the items
  - **WL 656 587 486**
    specifies 3 wavelengths, identified as **W1,W2,W3**
  - **YAN 0 10 20 40**
    specifies 4 fields, identified as **F1, F2, F3, F4**

- Sometimes, the data item is **Yes** or **No**
  - These can be entered as **Yes** or **No** or as Y or **N**
  - If the data is Yes, the Yes can be omitted(**Y** is assumed)
  - **PIM Y, RDM N, RDM** (same as **RDM Y**)

- Data items which are strings must be enclosed in quotes (single or double)
  - **TIT "Double Gauss F/2"**
  - **HEA 'WikiOptics'**

Index qualifiers and data

- Qualifiers or data separated by **|** means **OR**(only enter one)
  - **RDM Yes|No**

- Items in square brackets **[ ]** are optional
  - **SUR Sk|Si..j [F] [Zk]**

- Items followed by **[....z]** can take different values for different zoom positions
  - Assume there are zoom positions and RDY S3 is zoomed
    - **RDY Sk radius[....z]** syntax
    - **RDY S3 10 20 30** example
    - **RDY S3 Z2 25** example with Z qualifires
  - Also applies to **....f** and **....w**

A note on Numbers

- Exponential input may be used
  - 0.1E2 = 1.0E1 = 10

- Object, stop, and image surfaces can be called O, S, and I, respectively
  - SI image surface (can only be referenced by I)
  - SO object surface (can be zero or oh)
  - SS stop surface
  - SI-1 surface before the image surface

- 10^{13}(=1E13) is the default for INFINITY for object distance

Section 2

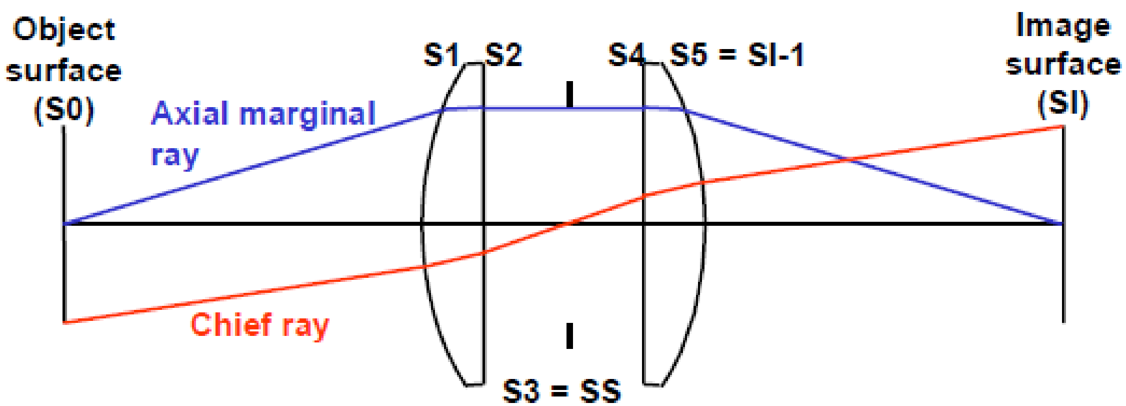
System data

System data

- Define ray bundles
- Minimum required
  - Pupil specification
    - EPD, FNO, NA, NAO
    - Wavelengths(at least one)
  - Field definition
    - Field angle, object heights, image heights

- Lens units
- Vignetting factors
- Gaussian apodization
- Through-focus definition
- Afocal specification
- Polarization data

Chief and marginal ray



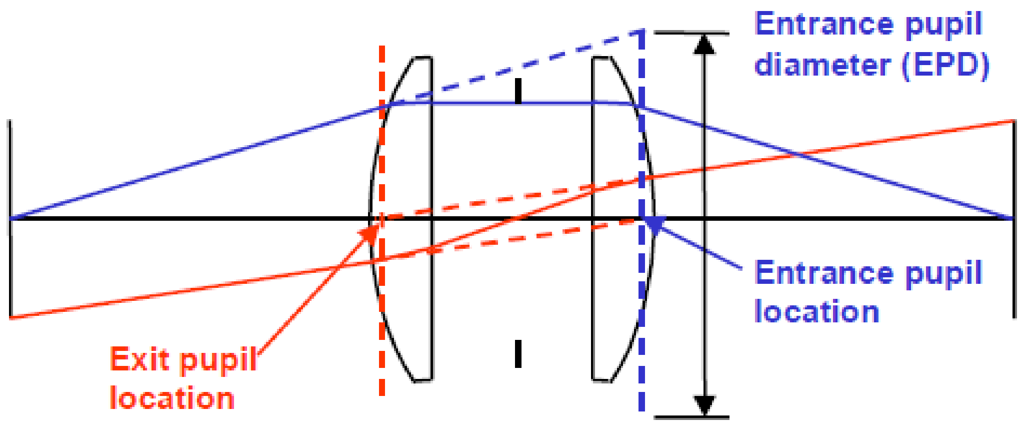
- Light initially travels from left to right and hits the surfaces in numbered order
- **Axial marginal ray** starts on-axis and goes through the edge of the aperture stop
- **Chief ray** starts off-axis and goes through the center of the aperture stop

Stops

from *Optics, Hecht*

- Aperture stop is any element that determines the amount of light reaching the image
- Entrance pupil is the image of the aperture stop as seen from an axial point on the object through those elements preceding the stop
- Exit pupil is the image of the aperture stop as seen from an axial point on the image plane through the interposed lenses

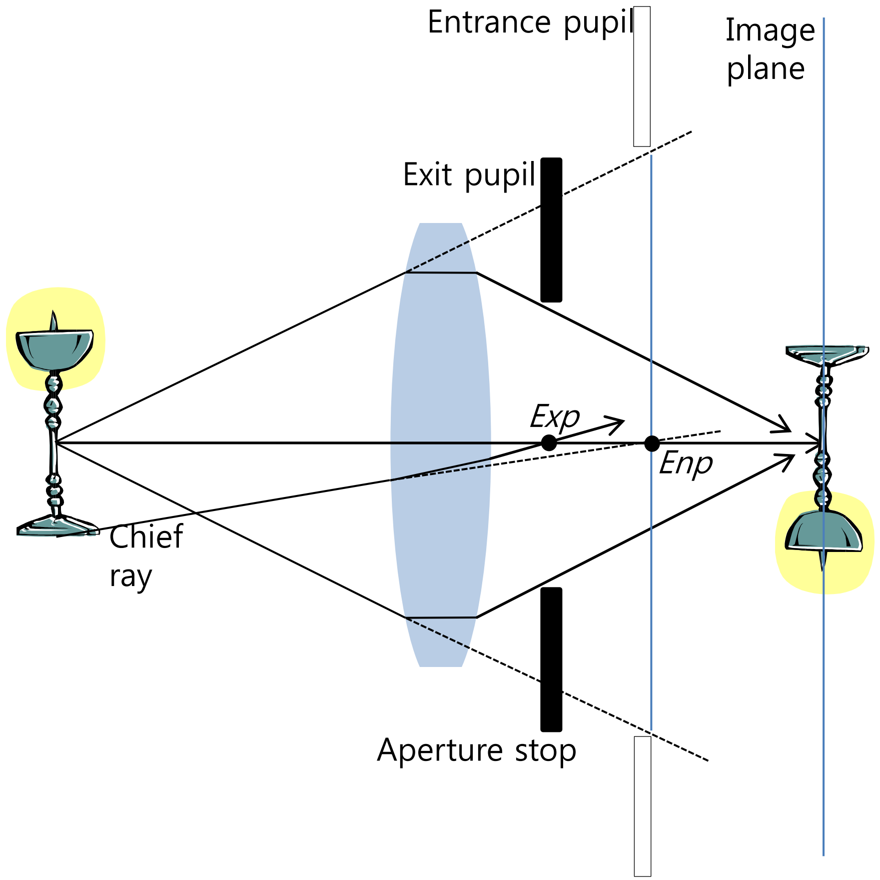
Stops



- The entrance pupil location is where the extension of the entering chief ray crosses the optical axis

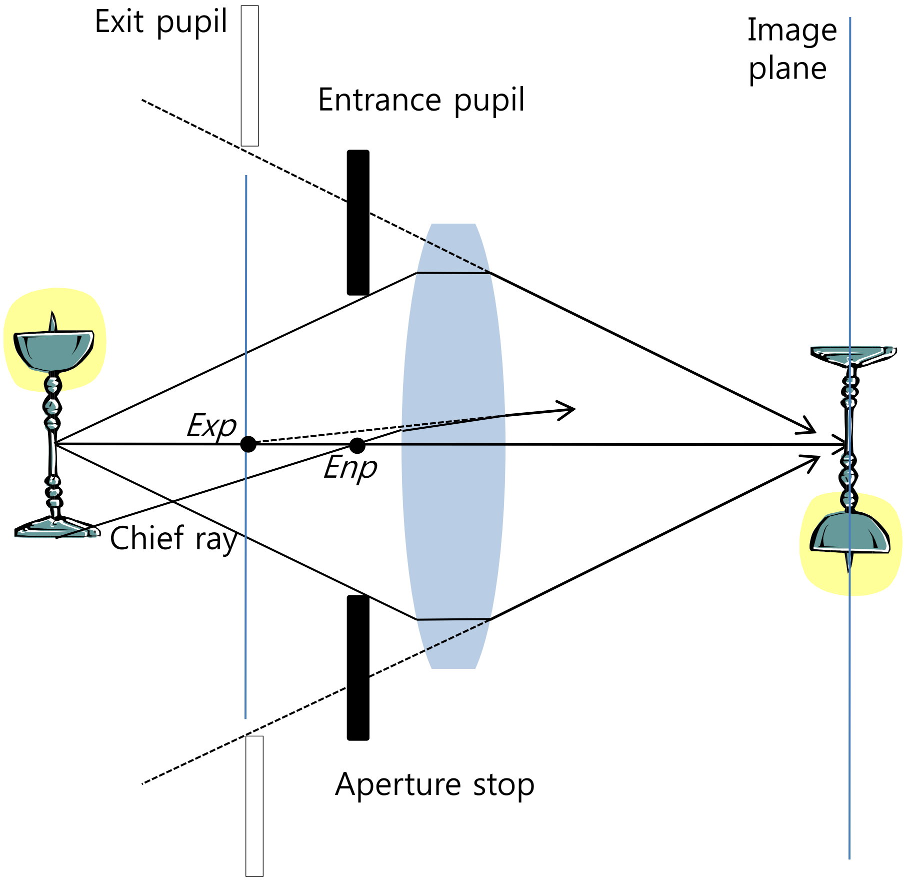
- The exit pupil location is where the extension of the exiting ray crosses the optical axis

Rear aperture stop



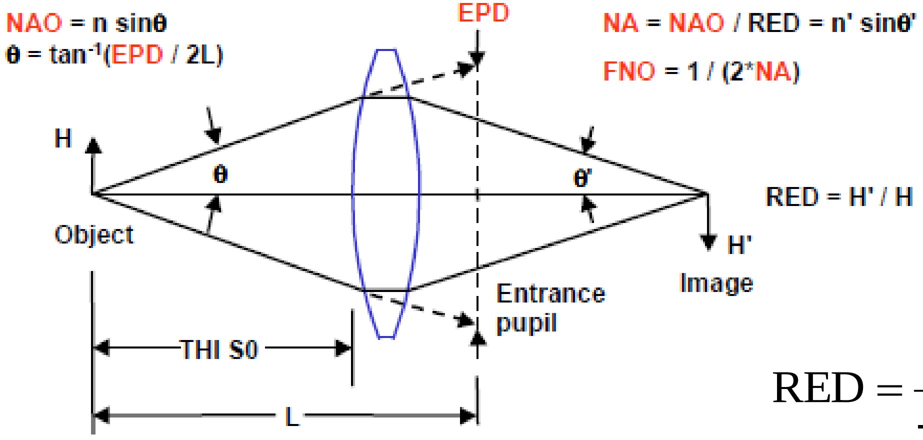
- Aperture stop itself serves as the exit pupil

Front aperture stop



- Aperture stop itself serves as the entrance pupil

Pupil specification



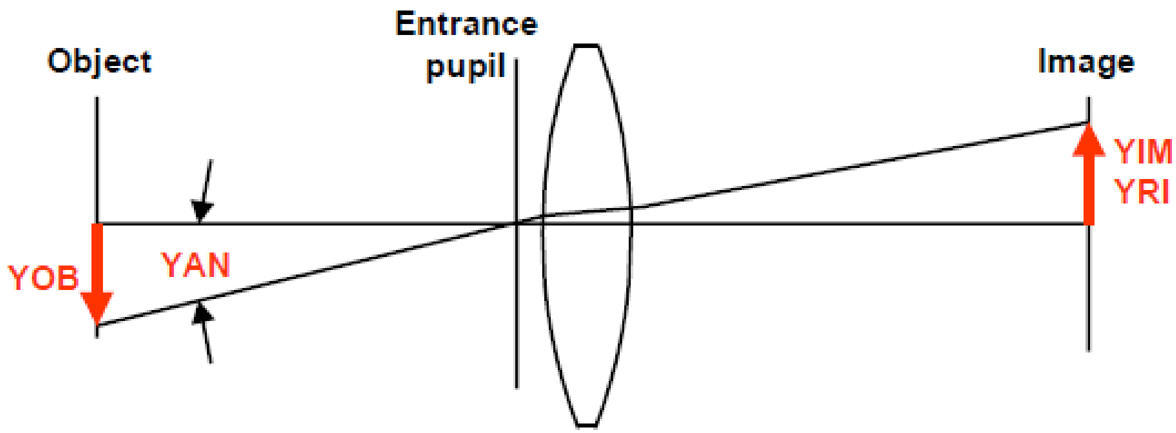
$$\mathrm{RED} = \frac{\text{Image height}}{-\text{Object height}} = -\mathrm{M}$$

- Entrance pupil diameter : **EPD**
- Numerical aperture at object : **NAO**
- Numerical aperture at image : **NA**
- F/number : **FNO**

Wavelength

- WL wavelength_nm….w
  - Enter up to 21 values in nanometers(nm)
  - Enter values descending order
  - One wavelength is designed to the reference wavelength
    - Used for first-order calculations and as default for single ray tracing
    - Default is middle wavelength (or left of middle)
  - **WL 650 546.07 450**

Wavelengths & field definition



- Field angle : **XAN, YAN** in degrees
- Object height : **XOB, YOB**
- Paraxial image height : **XIM, YIM**
- Real image height : **XRI, YRI**

Lens unit and system data list

- DIM I|C|M
  - I(nches), C(entimeters), or M(illimeters)
  - Same as DDM(immediate command)

  cf. SCA DIM [Si..j] I|C|M

- SPC [WL | APE | FLD | VIG | OTH]
  - Lists all system data (for first zoom position)
    - WL : Wavelength
    - APE : Aperture
    - FLD : Field
    - VIG : Vignetting
    - OTH : Other(FFO, IFO…)

Useful commands

- EVA macro_expression
  - EVA (EFL) ! Evaluate the effective focal length of the lens
  - EVA (EPD) ! Evaluate the entrance pupil diameter
  - EVA (Y F1 R2 SI) ! Evaluate the Y value at the image surface(SI) of ! the upper marginal ray(R2) for field 1(F1)

- WRI [U^unit_number] [Qformat_picture] [expression_list]
  - Allows you to output data to the screen display or to an opened file
  - Immediate command

```
CODE V> RES MYLENS
CODE V> ^x == 5
CODE V> WRI "The curvature of surface" ^x "is" (CUY S^x)
The curvature of surface 5 is 4.62243
```

- TOW;*commands*
  - Generates output in a tabbed output window
  - TOW;VIE;GO

Section 3

Basic lens data

RDY, THI and GLA

- RDY Sk y_radius [....z]
  - Spherical radius
  - Y-radius for non-rotationally symmetric surfaces
  - "0" means "infinity" (a plane surface)

- THI Sk thickness[....z]
  - Distance along the Z axis to the next surface

- GLA Sk [P] [glass_name [....z]]
  - GLA S2

    (Same as GLA S2 AIR)
  - GLA S5 BK7 ! Implies Schott
  - GLA S5 BK7_Hoya ! Hoya specified
  - GLA S3 517.642
  - GLA S5 1.517:64.2

GLA

- Fictitious glass
  - Only glass that can be vary in optimization
  - Designated by a decimal point
  - Defined by n_d and V_d

517.642 ! n_d=1.517, V_d=64.2
72235.293104 ! n_d=1.72235 V_d=29.3104

  - Uses a normal partial dispersion model

- n_d
  - refractive index at helium d-line (0.5876um)

- V_d
  - Abbe V-number
  - $$V_d = \frac{n_d - 1}{n_F - n_C}$$

Glass manufactures

- **Glass manufactures included in CODEV**

CHANCE - Chance-Pilkington

CHINA - Chinese glass catalog

CORNFR - Corning France (formerly Sovirel)

CORNING - Corning Glass

HOYA - Hoya Corporation

HIKARI - Hikari Glass Co.

KODAK - Eastman Kodak Co.

NSG - Nippon Sheet Glass GRIN materials catalog

OHARA - Ohara Corporation

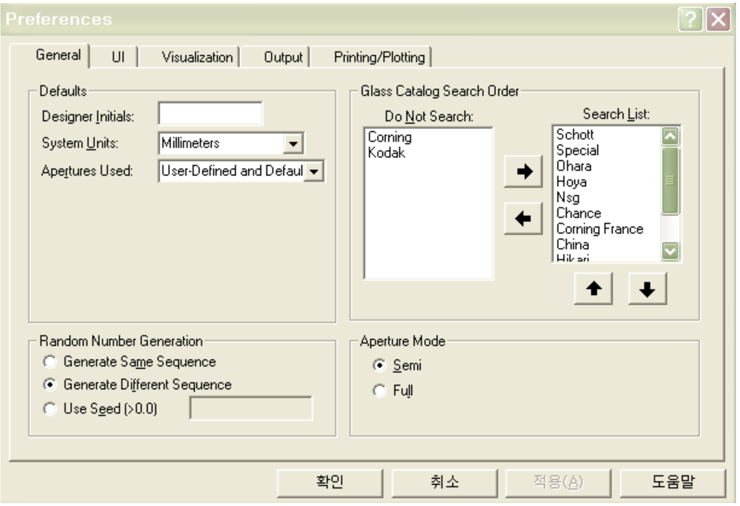
PILKINGTON - Pilkington Optical Glasses

SCHOTT - Schott Glass Technologies, Inc.

SPECIAL - CODE V special materials catalog (IR, UV, etc.)

(SILICA for fused silica)

SUMITA - SUMITA Optical Glass, Inc.

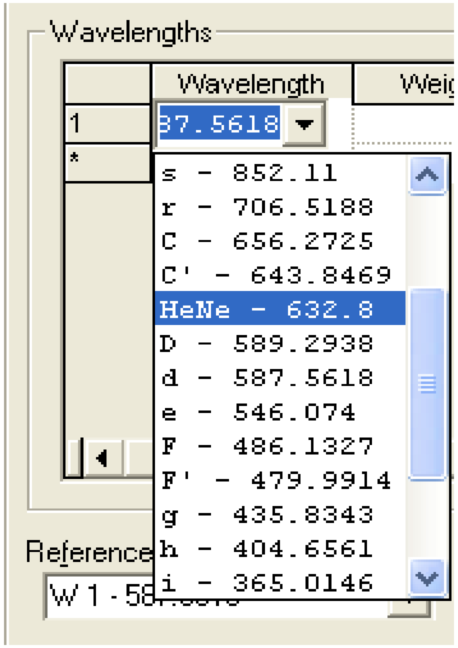


Special wavelength

- **Fraunhofer lines and other standard lines**
  (from *MIL-HDBK-141*)

Color	Line	Wavelength (microns)	Element
Infrared		1.0140	Hg
Red	A′	0.7665	K
Red	C	0.6563	H
Yellow	D	0.5893	Na
Yellow	d	0.5876	He
Green	e	0.5461	Hg
Light Blue	F	0.4861	H
Blue	g	0.4358	Hg
Dark Blue	G′	0.4340	H
Violet	h	0.4047	Hg
Ultraviolet		0.3650	Hg

- **CODEV**



S

- S | Sk | Si..j [y_rad_curv thickness [glass_name]]
  - Provides three functions separately or together
    - Move surface pointer
    - Replace curvature/radius, thickness, glass
    - Insert surfaces

- When CODE V processes a surface-related command, it uses a surface pointer to know which surface on which to perform a command.

- The pointer refers to the surface that was referenced on the last input operation.

S

Surface pointer

```
-sur sa
                 RDY             THI        RMD          GLA
   OBJ:        INFINITY        INFINITY
 > STO:        INFINITY        0.000000
   IMG:        INFINITY        0.000000
```

Insert Surface S2

```
-s2
     Surface pointer = 2
-sur sa
                 RDY             THI        RMD          GLA
   OBJ:        INFINITY        INFINITY
   STO:        INFINITY        0.000000
 >   2:        INFINITY        0.000000
   IMG:        INFINITY        0.000000
```

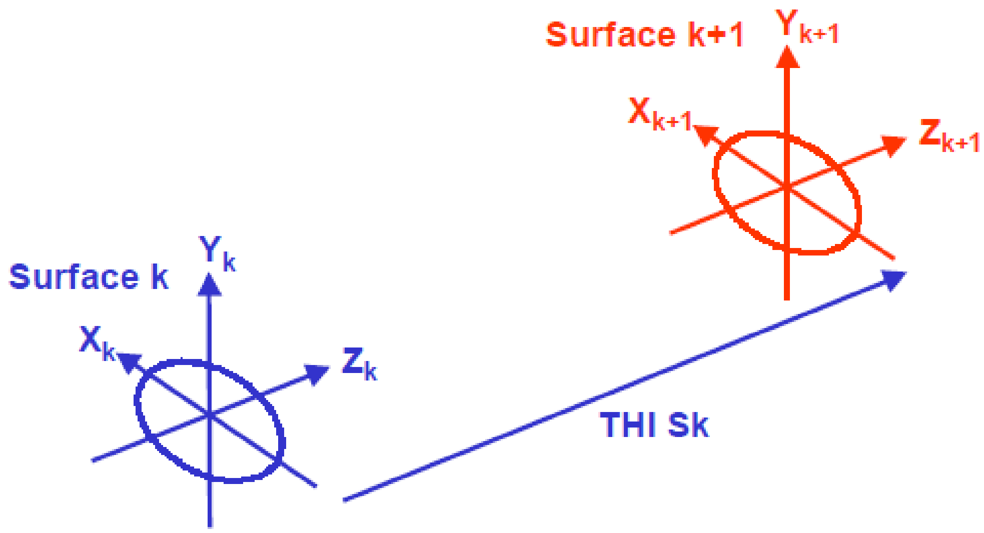
Insert Surface S3 with RDY and THI

```
-s3 10 2
  SURFACE   3:
          RDY 10.000000    ; THI      2.000000 ; GLA  AIR
-sur sa
                 RDY             THI        RMD          GLA
   OBJ:        INFINITY        INFINITY
   STO:        INFINITY        0.000000
     2:        INFINITY        0.000000
 >   3:        10.00000        2.000000
   IMG:        INFINITY        0.000000
```

Move surface pointer to S1

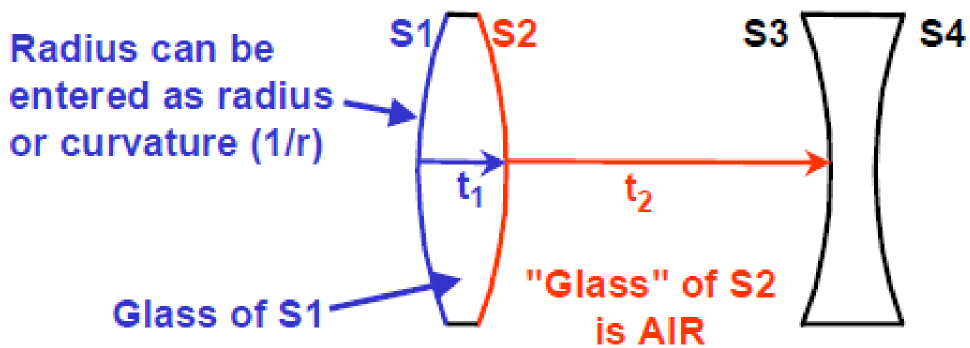
```
-s1
     Surface pointer = 1
-sur sa
                 RDY             THI        RMD          GLA
   OBJ:        INFINITY        INFINITY
 > STO:        INFINITY        0.000000
     2:        INFINITY        0.000000
     3:        10.00000        2.000000
   IMG:        INFINITY        0.000000
```

Surface coordinate



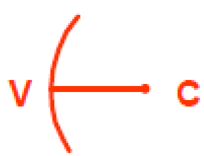
- Right handed
- Z axis is optical axis
- Local x, y, z coordinate system at each surface

Surface definition

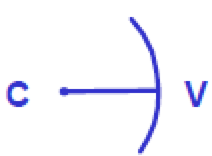


t_1 = thickness of surface 1

t_2 = thickness of surface 2
(actually a spacing)



Center of curvature to RIGHT of surface = **Positive**



Center of curvature to LEFT of surface = **Negative**

Section 4

Learning from reference lenses

Starting new lens

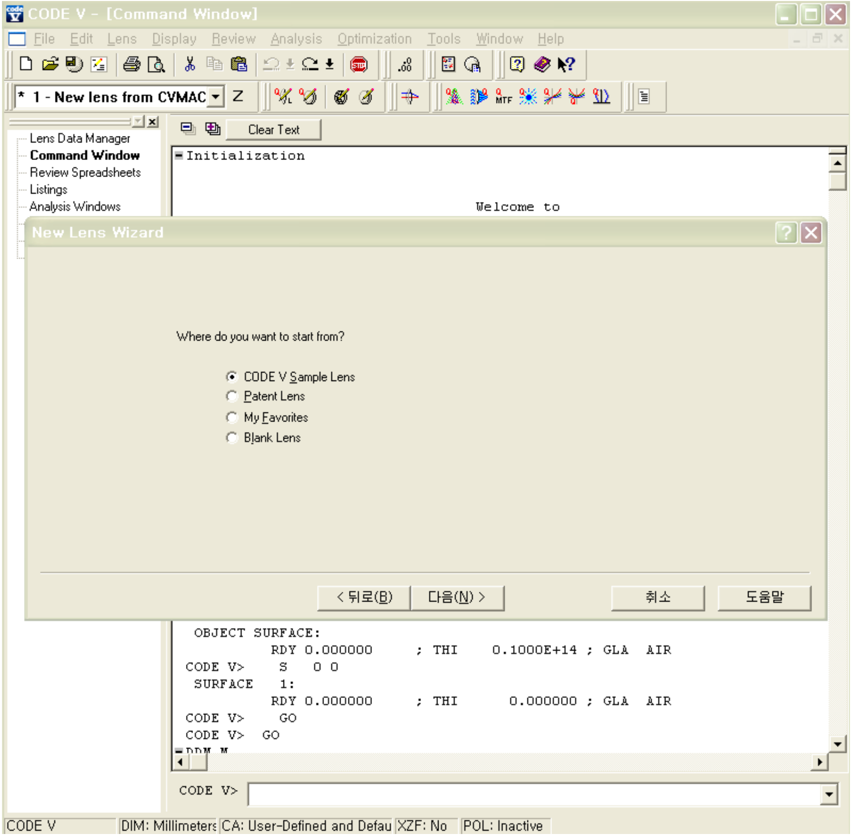
- **LEN [NEW]**
  - Starts a new lens and initializes new lens defaults
  - When you create a new lens, CODE V automatically executes a macro named cvnewlens.seq
  - On the command line, you must use the NEW qualifier to execute this macro

- Starting the New Lens Wizard
  - CODE V sample lenses
  - Patent lens
  - My favorites
    - Choose the Tools>Add To Favorites menu when you have the lens open in CODE V
  - Blank lens ; Same as LEN NEW

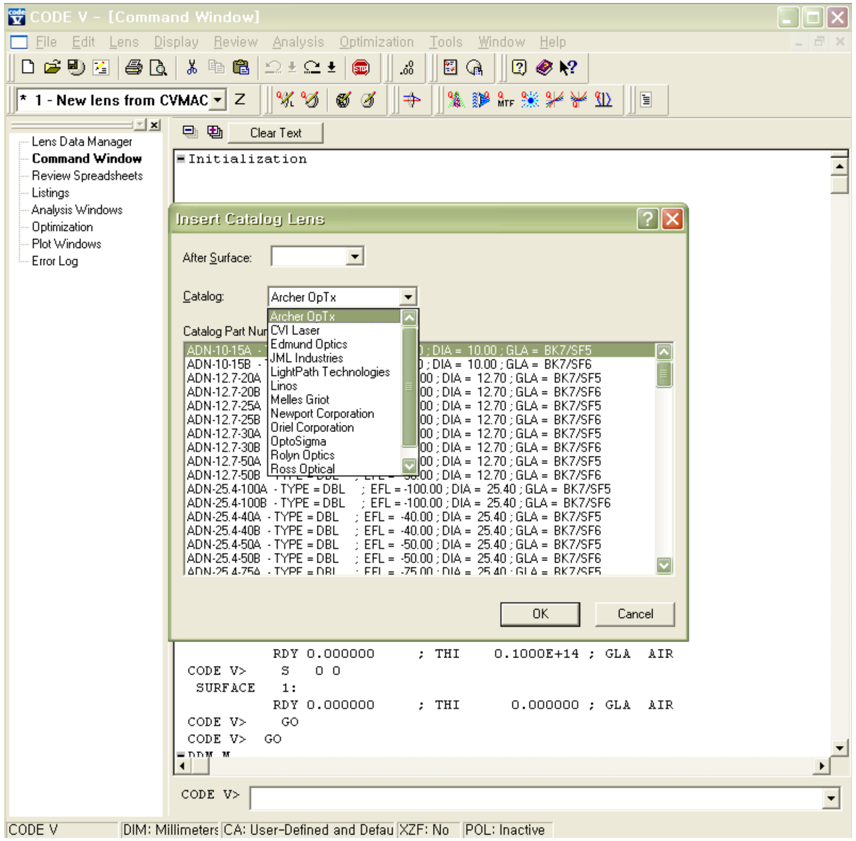
- Optical supplier's lens catalog

Starting new lens

File>New>New lens wizard lens

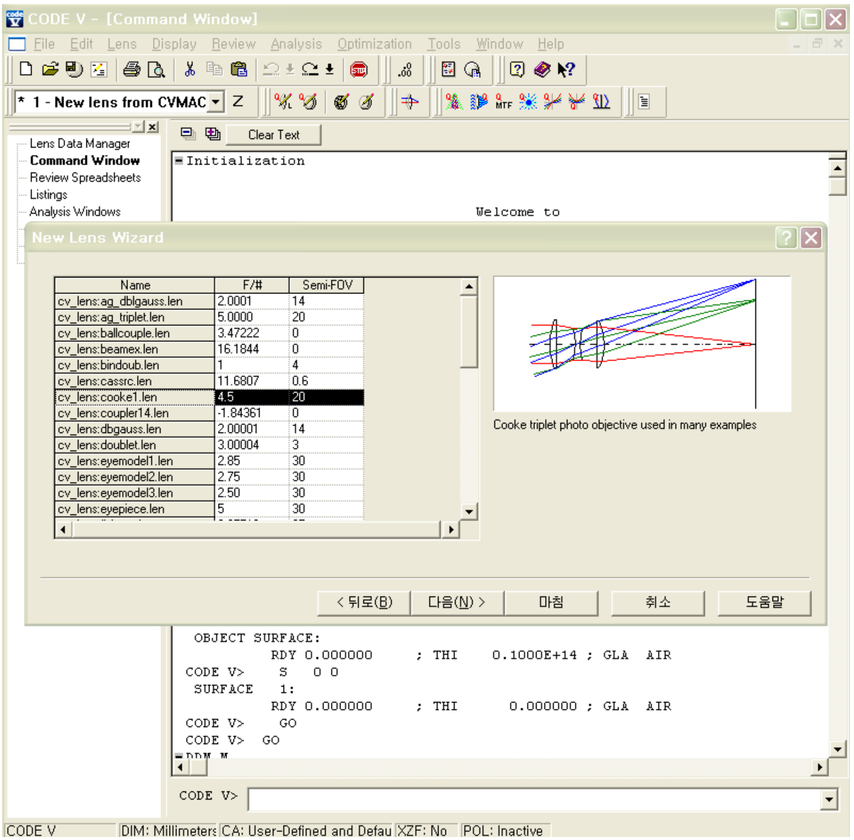


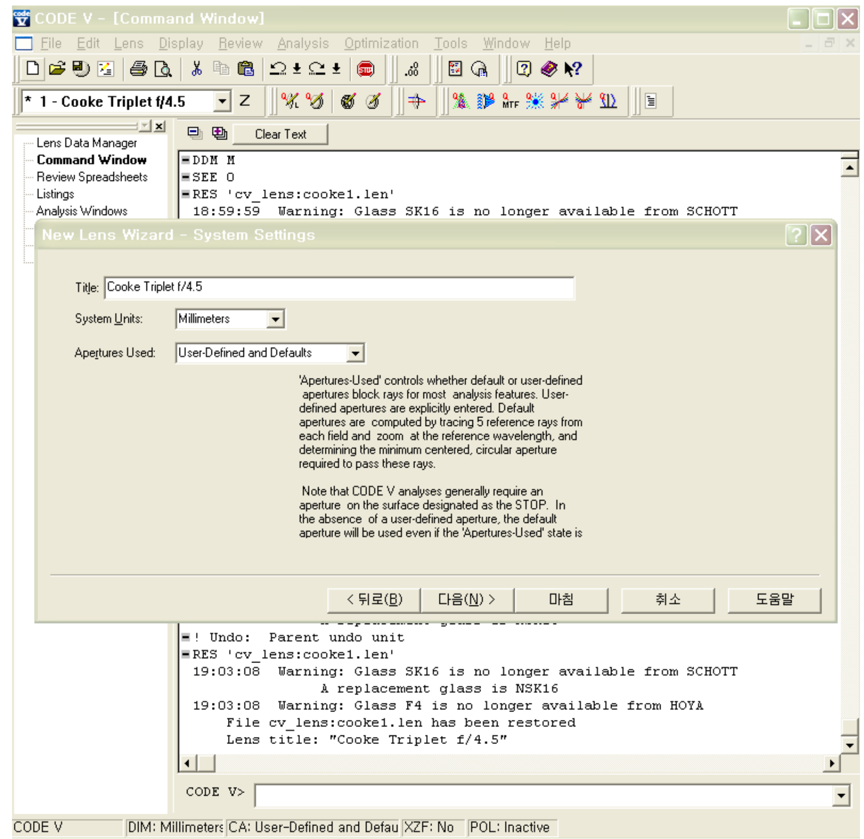
Edit>Insert catalog lens



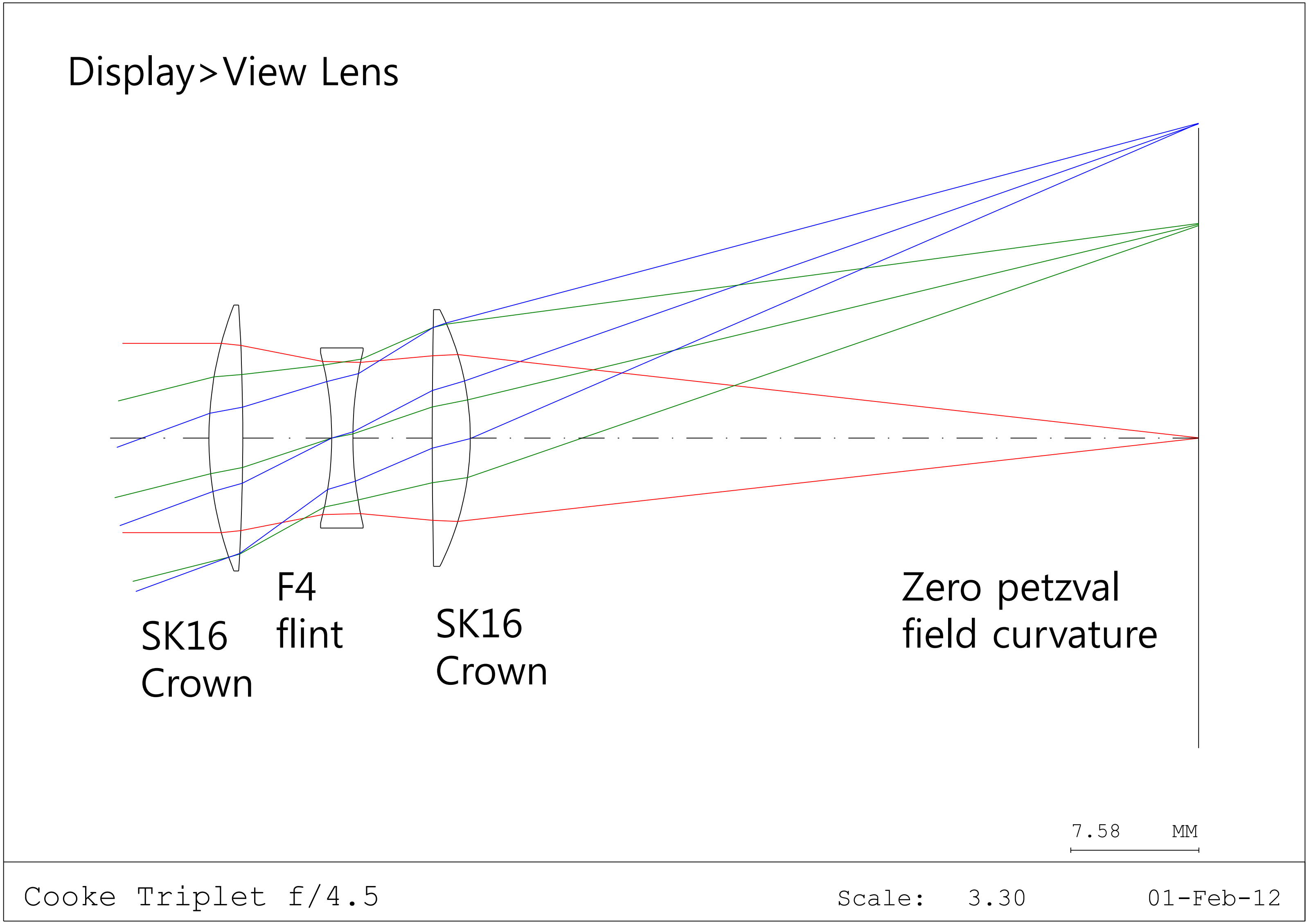
Starting new lens

Open Cooke Triplet f/4.5 using the new lens wizard





Cooke Triplet f/4.5



List lens data

- **LIS**
  - List all lens data including the lens title and data
  - Surface data(**SUR**)
  - System data(**SPC**)
  - Aperture data(**APE**)
  - Non-sequential data(**NSL**)
  - Private catalog(**PVC**)
  - Index of refraction data(**IND**)
  - Solves(**SOL**)
  - Zoomed data(**ZLI**)
  - First-order data(**FIR**)

```
-spc

SPECIFICATION DATA
   FNO        4.50000
   DIM             MM
   WL          656.30      546.10      486.10
   REF              2
   WTW              1           2           1
   XAN        0.00000       0.00000       0.00000
   YAN        0.00000      14.00000      20.00000
   WTF        1.00000       1.00000       1.00000
   VUY        0.00000      -0.01406       0.16171
   VLY        0.00000       0.06883       0.24355
   POL           N
```

SUR

- **SUR Sk | Si..j [F] [Zk]**
  - Lists surface data (default is first zoom position) for designated surface(s) ; if Sk | Si..j is omitted, surface pointer supplies Sk
  - Omit F : All data types for that surface(s), except control variable/coupling codes
  - F : Include all data types and control codes
  - **SUR SA F**

    : Lists all surface data plus variable control codes and special glass data

```
sur sa f
              RDY              THI      RMD        GLA          CCY     THC     GLC
> OBJ:      INFINITY         INFINITY                           100     100
     1:     21.48138         2.000000          SK16_SCHOTT      100     100
     2:   -124.10000         5.260000                           100     100
   STO:    -19.10000         1.250000          F4_HOYA          100     100
     4:     22.00000         4.690000                           100     100
     5:    328.90000         2.250000          SK16_SCHOTT      100     100
     6:    -16.70000        43.050484                           100     PIM
   IMG:     INFINITY         0.028933                           100       0
```

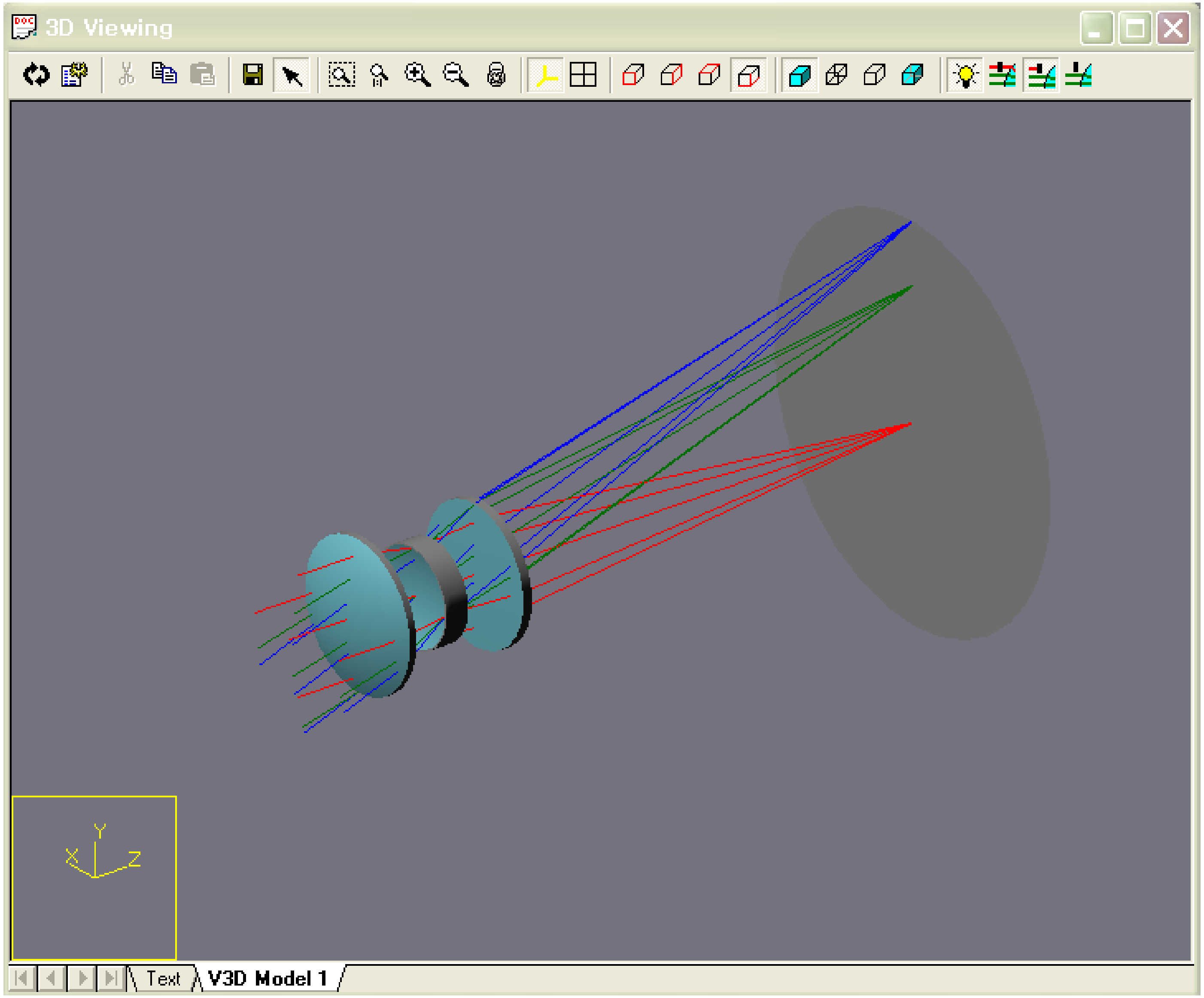
- **FIR**
  - Lists table of first-order system parameters for all zoom position
  - At any conjugate, finite or infinite
    - EFL : Effective focal length
    - BFL : Back focal length
    - FFL : Front focal length
    - FNO : f/number
    - IMG DIS : Actual image distance (SI-1 to SI)
    - OAL : Overall length(S1 to SI-1)
  - Paraxial image
    - HT : Height on image surface
    - YAN : Last field angle(in degrees)
  - Entrance pupil
    - DIA : Diameter
    - THI : Distance from S1 to pupil
  - Exit pupil
    - DIA : Diameter
    - THI : Distance form SI-1 to pupil

```
fir

 INFINITE CONJUGATES
    EFL           50.0004
    BFL           43.0505
    FFL          -39.5680
    FNO            4.5000
    IMG DIS       43.0794
    OAL           15.4500
    PARAXIAL IMAGE
     HT           18.1986
    ANG           20.0000
    ENTRANCE PUPIL
     DIA          11.1112
     THI           8.2156
    EXIT PUPIL
     DIA          11.6267
     THI          -9.2694
```

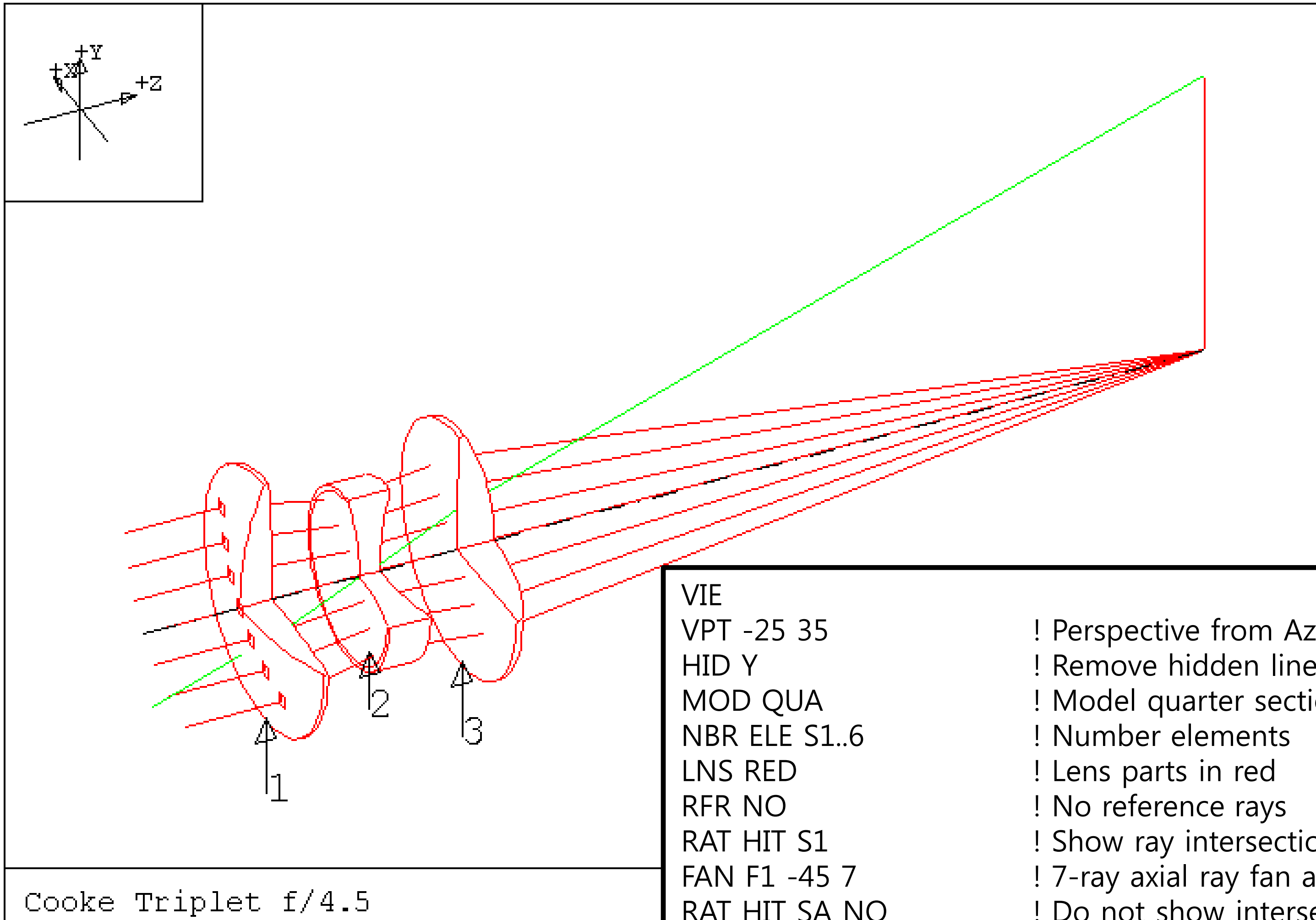
FIR

- **FIR**
  - Add at finite conjugates (if applicable)
    - RED : Reduction ratio
    - FNO : f/number at actual conjugate
    - OBJ DIS : Object distance (SO)
    - TT : Total track distance (SO to SI)
  - Paraxial image
    - THI : Paraxial image distance(from SI-1)
  - Add, for zoomed systems
    - STO DIA : Ray traced diameter of axial bundle on stop surface(SS)

3D viewing V3D



View lens VIE




```
VIE
VPT -25 35          ! Perspective from Az=-25 deg, el=35 deg
HID Y               ! Remove hidden lines
MOD QUA             ! Model quarter section
NBR ELE S1..6       ! Number elements
LNS RED             ! Lens parts in red
RFR NO              ! No reference rays
RAT HIT S1          ! Show ray intersections on s1
FAN F1 -45 7        ! 7-ray axial ray fan at -45 degr.
RAT HIT SA NO       ! Do not show intersections for rays to follow
RAT COL GRE         ! Following rays green
RSI F3 0 0          ! Draw chief ray from f3
LAB VAX             ! Label view axes
GO
```

Section 5

Analysis I

Analysis

- Paraxial ray trace (FIO)
- Real ray trace (RSI, SIN)
- Ray aberration curves(RIM)
- Field curves (FIE)
- Modulation transfer function(MTF)

FIO [Sk | Si..j] [Zk]

- Lists paraxial data for marginal and chief rays
- The output of the FIO command is six columns of data. These are the ray height(H), ray angle (U, in radians), and refractive index(N) times angle of incidence(I), all given for both paraxial rays.

Cooke Triplet f/4.5

Position 1, Wavelength = 546.1 NM

	HMY	UMY	N * IMY	HCY	UCY	N * ICY
EP	5.555594	0.000000		0.000000	0.363970	
1	5.555594	-0.099261	0.258624	-2.990225	0.277703	0.224769
2	5.357073	-0.187974	-0.231141	-2.434820	0.462893	0.482513
STO	4.368329	-0.028411	-0.416682	0.000000	0.285635	0.462893
4	4.332815	0.076177	0.273123	0.357044	0.472965	0.489194
5	4.690086	0.041467	0.090437	2.575249	0.288434	0.480795
6	4.783387	-0.111111	-0.397541	3.224225	0.347834	0.154766
IMG	-0.003215	-0.111111		18.208703	0.347834	

Marginal ray data (HMY, UMY, N * IMY) — **Chief ray data** (HCY, UCY, N * ICY)

Tracing single rays

- Two types of single rays
  - RSI : relative single ray (relative in pupil and field)
  - SIN : single ray (arbitrary ray)

- When tracing single rays, blocking apertures are ignored
  - Ray traces to image surface (if it can)
  - A or O code in output indicates if ray was blocked by a clear aperture or an obscuration
  - E code in output indicates an edge thickness violation (virtual ray tracing)

RSI ray trace

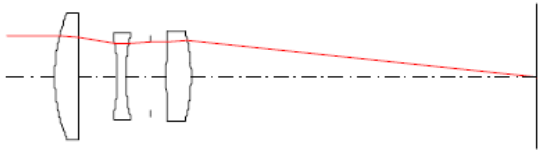
- RSI [Sk|Si..j] [Zn] [Wm] X_R Y_R θ_{XR} θ_{YR}
  - X_R Y_R : relative entrance pupil coordinates
  - θ_{XR} θ_{YR} : relative field in X and Y

- Ray defined as relative position in entrance pupil(pupil radius=1) and relative to defined fields(maximum field=1)

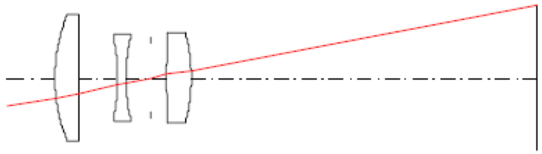
- The chief ray is traced first to determine pupil location
  - If chief ray fails, the requested real ray is not traced

Examples of RSI ray trace

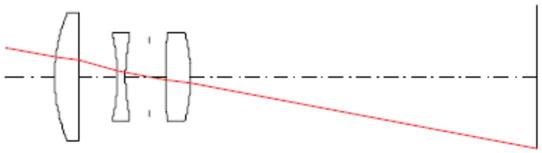
- Trace on-axis marginal ray
  RSI 0 1 0 0



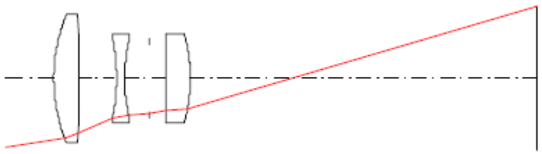
- Trace chief ray at full Y field
  RSI 0 0 0 1



- Trace chief ray at negative full field Y
  RSI 0 0 0 -1



- Trace lower marginal ray at full field in Y
  RSI 0 -1 0 1



Use of R and F qualifiers with RSI

- F qualifier can be used to specify field
  - Refers to one of the fields specified in the LDM
  - RSI Fk X_R Y_R
  - Examples

    RSI F1 0 1 ! on-axis marginal ray

    RSI F3 0 0 ! chief ray for field 3

- R qualifier can be used to refer to a reference ray(R1 to R5)
  - RSI Fk Rj
  - Examples

    RSI F1 R2 ! on-axis marginal ray

    RSI F3 R1 ! chief ray at field 3

- R qualifier can only be used in conjunction with an F qualifier

Ray trace output

- X Y Z ray coordinates on surface
  L M N ray direction cosines after refraction or reflection
  TNX TNY ray direction tangents after refraction or reflection
  AOI AOR angle of incidence and refraction
  LEN geometrical ray length from the previous surface
  SRL SRM SRN direction cosines of surface normal
  - Default is X Y Z TNX TNY LEN

- Outputs are selected by the command ROF(ray output format)
  ROF X Y Z AOI
  - ROF command by itself restores the defaults

- You can also specify the number of digits in the output
  - ROF 'F8.5' 8 digits, 5 after the decimal
  - ROF 'F12.8' 12 digits, 8 after the decimal

Examples

- RSI R1 F3

```
Cooke Triplet f/4.5
Position  1, Wavelength =   546.1 NM
              X           Y           Z          TANX        TANY       LENGTH
OBJ       0.00000   -0.364E+10    0.00000     0.00000     0.36397
  1       0.00000     -3.13684    0.23026     0.00000     0.27763     0.24504
  2       0.00000     -2.65339   -0.02837     0.00000     0.50174     1.80723
STO       0.00000      0.00000    0.00000     0.00000     0.28797     5.91670
  4       0.00000      0.36082    0.00296     0.00000     0.51726     1.30388
  5       0.00000      2.79134    0.01185     0.00000     0.29121     5.29027
  6       0.00000      3.34459   -0.33835     0.00000     0.34759     1.97873
IMG       0.00000     18.43624    0.00000     0.00000     0.34759    45.96586
                         OPD =    0.000 Waves
```

- INS S1; ROF X Y Z AOI; RSI R1 F3

```
Cooke Triplet f/4.5
Position  1, Wavelength =   546.1 NM
              X           Y           Z        ANG INC
OBJ       0.00000   -0.364E+10    0.00000
  1       0.00000     -3.22065    0.00000    20.00000
  2       0.00000     -3.13684    0.23026    11.60329
  3       0.00000     -2.65339   -0.02837    16.74128
STO       0.00000      0.00000    0.00000    26.64480
  5       0.00000      0.36082    0.00296    17.00473
  6       0.00000      2.79134    0.01185    27.83679
  7       0.00000      3.34459   -0.33835     4.68312
IMG       0.00000     18.43624    0.00000    19.16702
                         OPD =    0.000 Waves
```

SIN ray trace

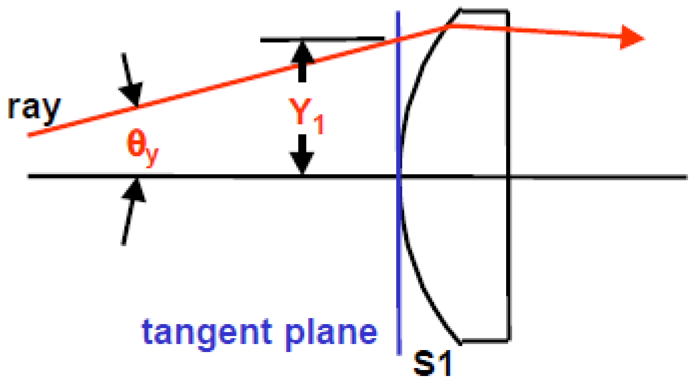
- Rays is defined by x, y, position on tangent plane to surface 1 and by its x, y direction tangents

- Particularly useful as a diagnostic if chief rays fail to trace

- SIN [Sk|Si..j] [Zn] [Wm] X_1 Y_1 tanθx tanθy

  X_1 Y_1 coordinates on tangent plane to surface 1

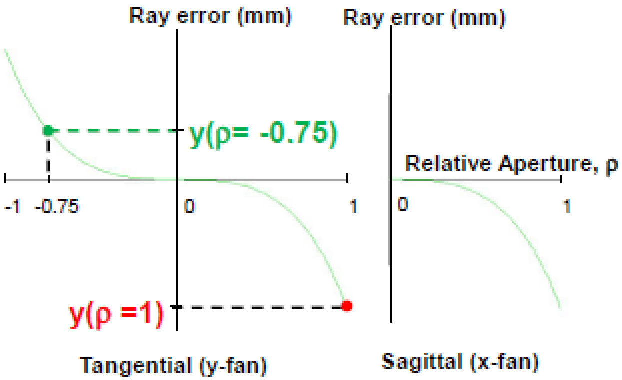
  tanθx tanθy direction tangents in x and y

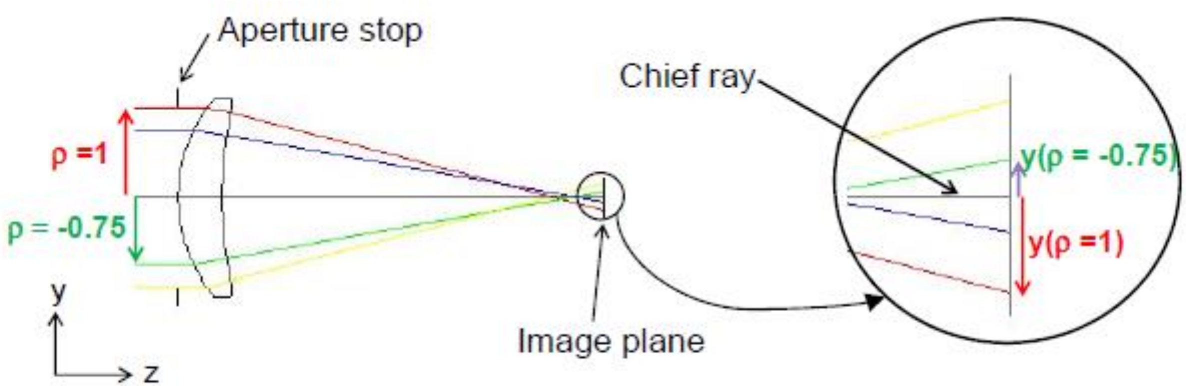


Ray aberration curves (RIM)

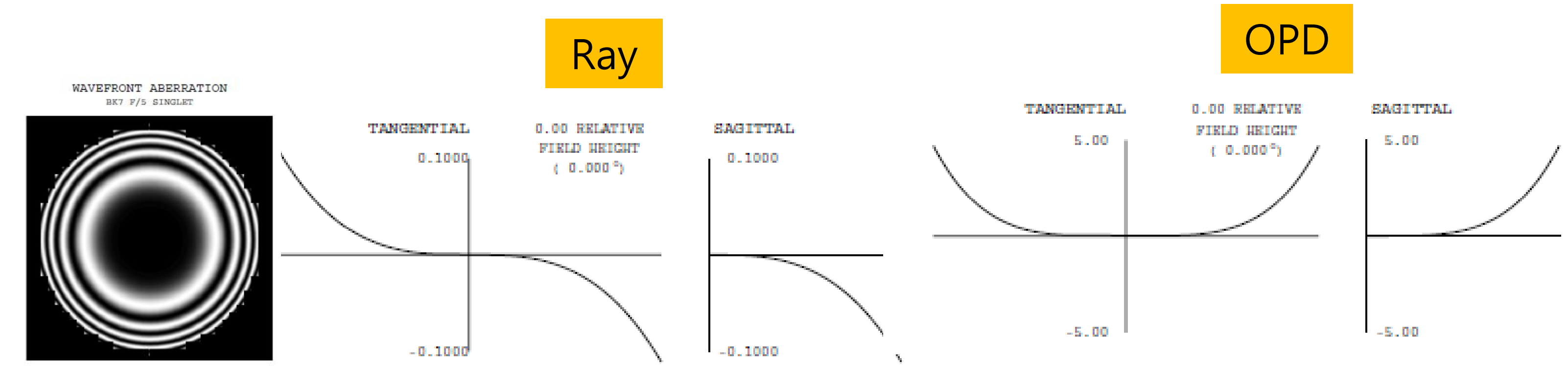
- Vertical axis : distance on image plane between chief ray and current ray

- Horizontal axis : relative height of ray in aperture stop (or entrance/exit pupil)

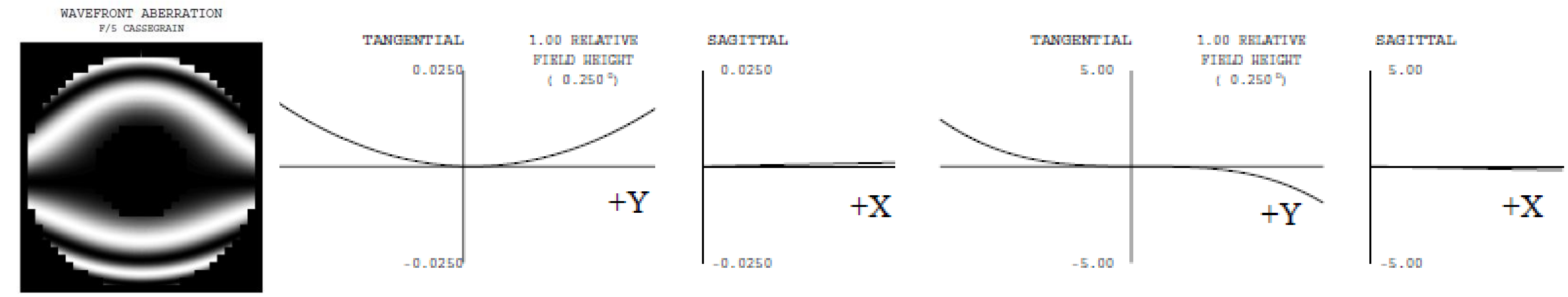




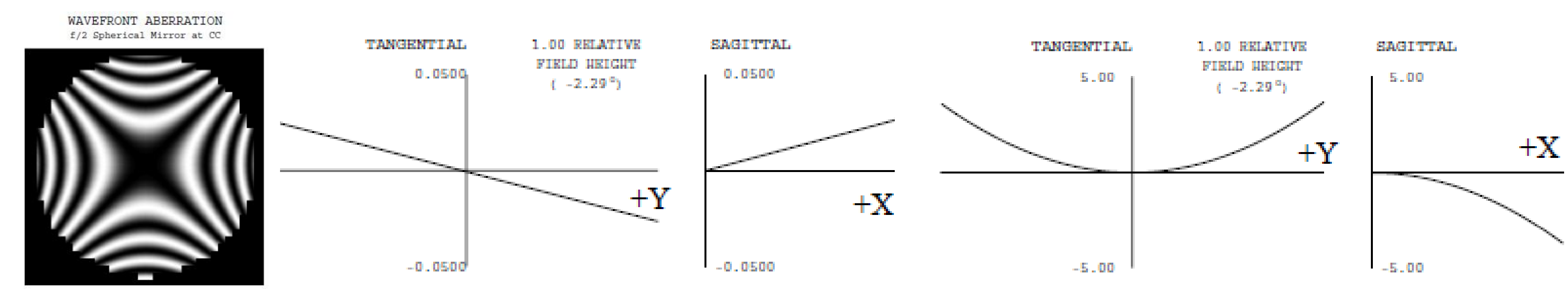
Typical ray and OPD aberration curves



Spherical aberration

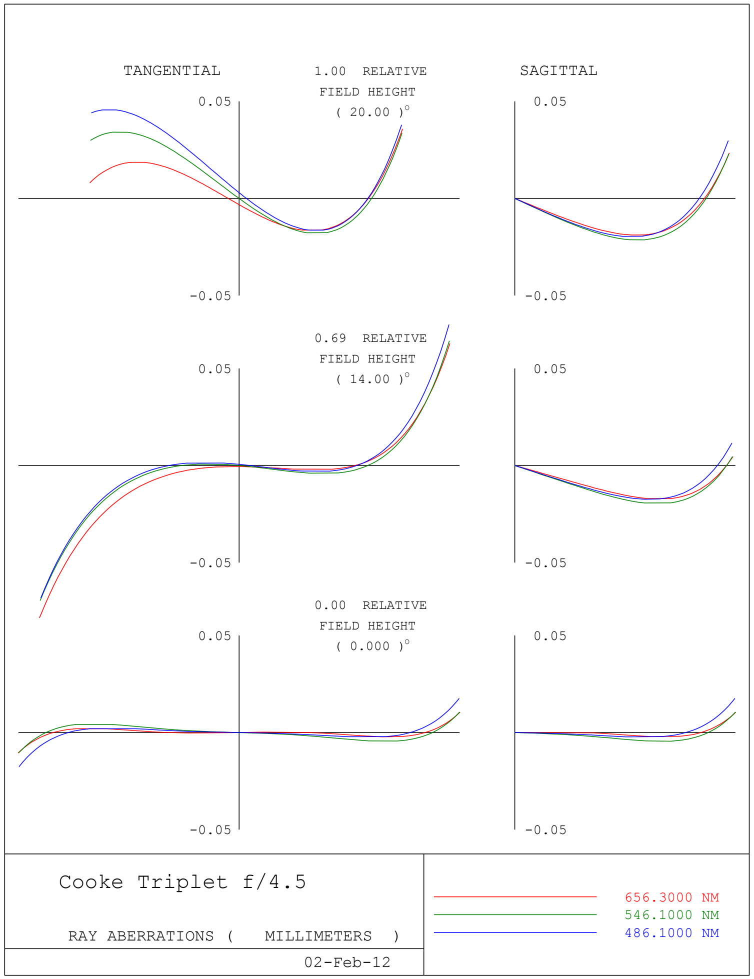


Coma

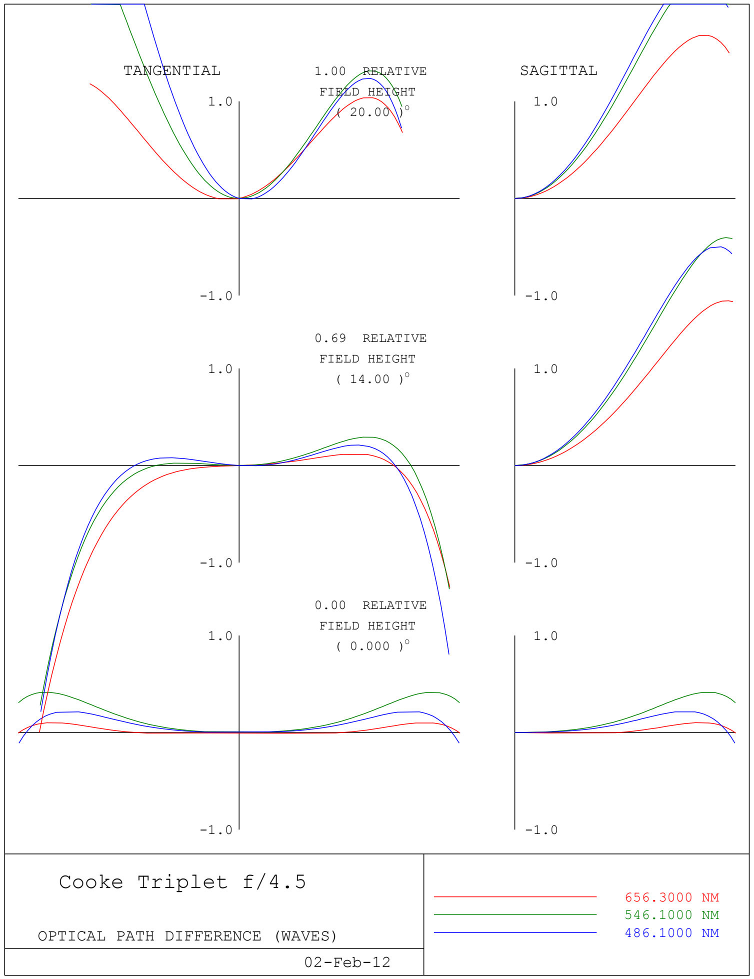


Astigmatism

Ray/OPD aberration plots (RIM)

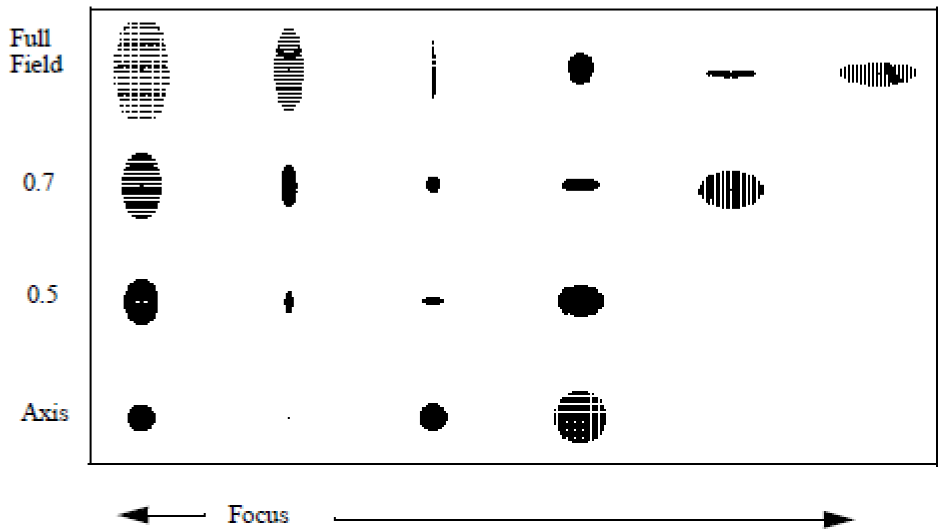


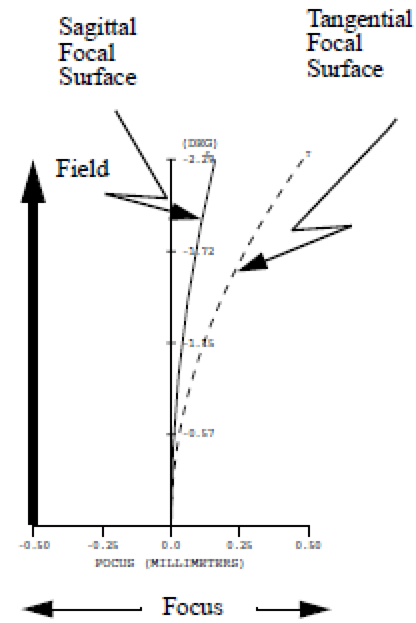
Ray aberration plot



OPD aberration plot

Field curves (FIE)





- As frequently used by the designer as are rim ray plots, astigmatic field curve plots provide a quick look at the astigmatism (and field curvature) in a system

- The medial focal surface (the position of best diffraction focus) lies midway between the sagittal and the tangential focal surfaces

- The amount of astigmatism is proportional to the axial distance between the sagittal and tangential focal surface

Spherical aberration

- LA′ : Longitudinal spherical aberration, TA'_R : Transverse spherical aberration

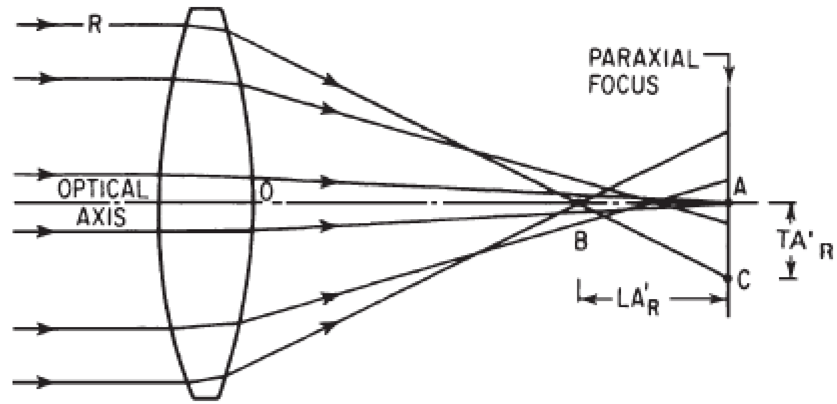


Fig. A simple converging lens with undercorrected spherical aberration. The rays farther from the axis are brought to a focus nearer the lens.

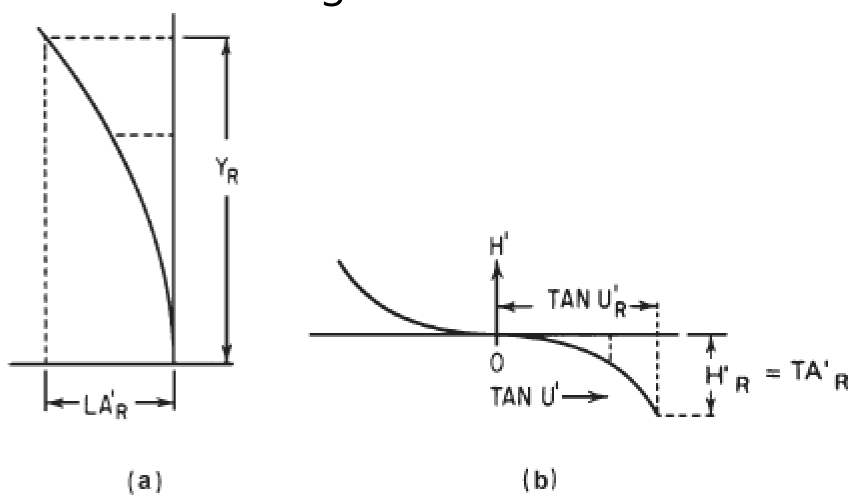


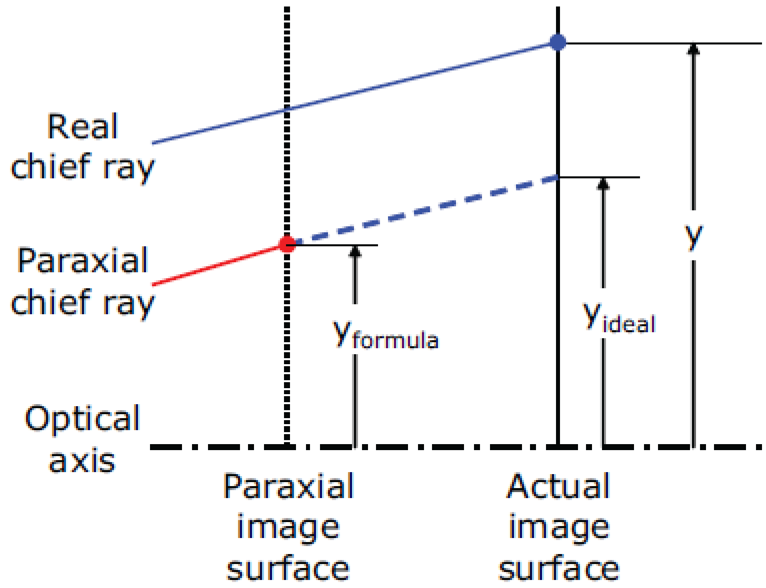
Fig. Graphical representation of spherical aberration

From "Modern optical engineering, Smith

Distortion

- Distortion does not result in a blurred image and does not cause a reduction of image quality such as MTF

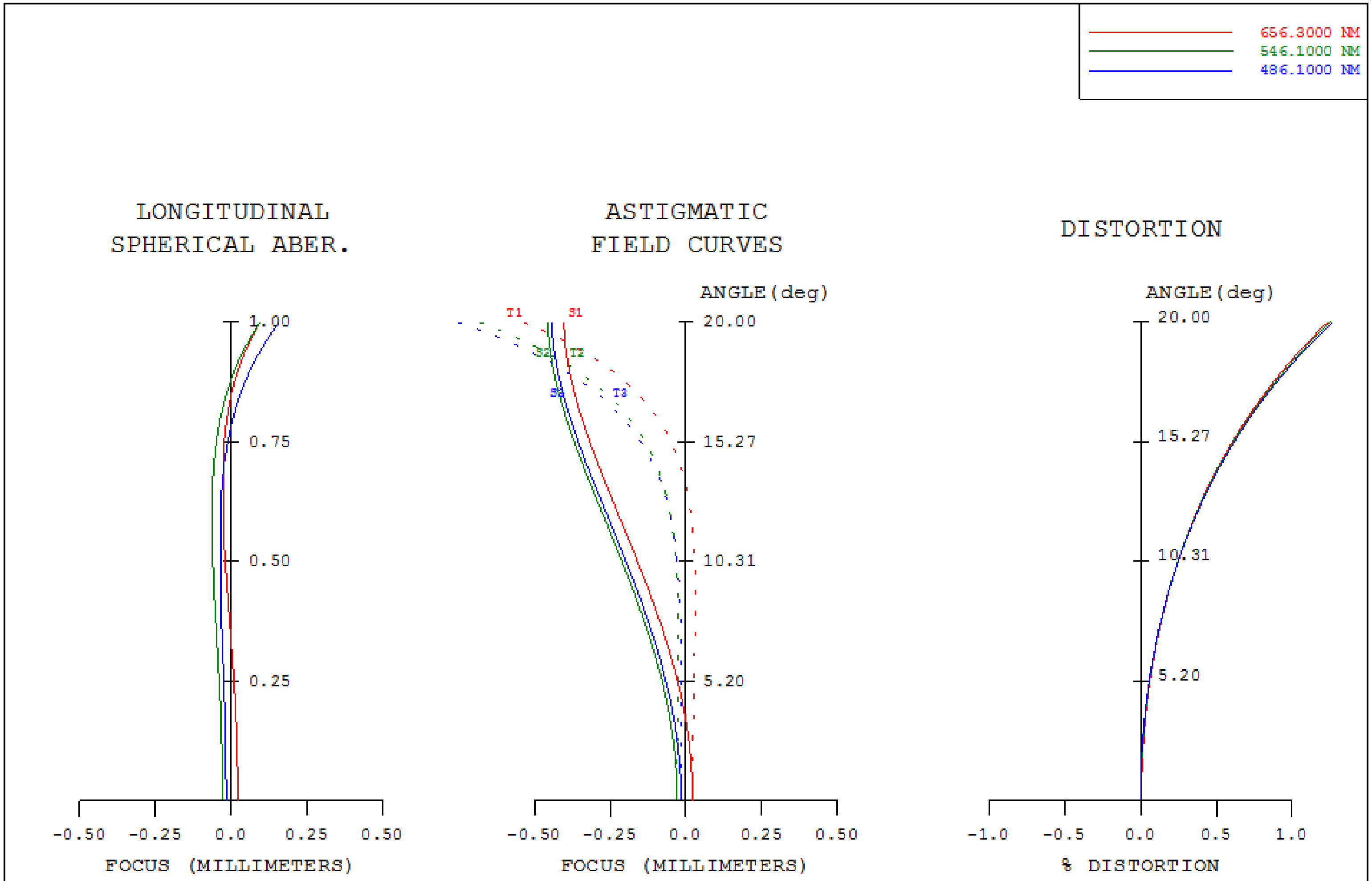
$$\text{Percent Distortion} = \frac{(\text{real chief ray height}) - (\text{paraxial chief ray height})}{\text{paraxial chief ray height}} \times 100$$



Note: The slope of the dashed line is equal to that of the <u>real</u> chief ray

DIY = $(y - y_{ideal})/y_{ideal}$
Used in AUT, FIE, and uncalibrated FMA*
Note: $y_{formula}$ = EFL·tan(YAN) or −RED·YOB
*FMA formerly used $y_{formula}$ instead of y_{ideal}

FIE



FIE
DST CHR 1.0 ! ± 1.0% maximum plotted distortion, show chromatic effects
AST CHR 0.5 ! ± 0.5 mm maximum plotted astigmatism, show chromatic effects
LSA 0.5 ! ± 0.5 mm maximum plotted LSA
GO

Modulation Transfer Function (MTF)

- Start with black and white bars (or sinusoid) with specified frequency (default : sinusoid)

- Frequency in "lines/mm," where "lines"="line pairs"(1 black line + 1 white line)=1 cycle

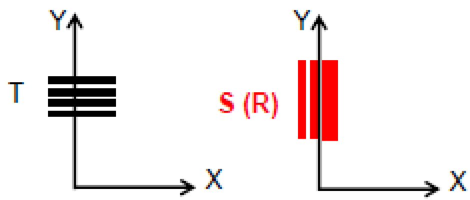
- Modulation=contrast

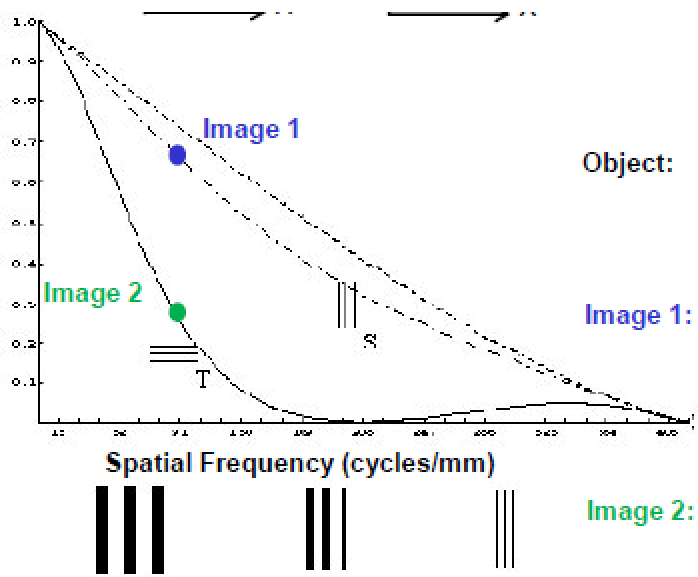
$$\boxed{\begin{aligned} &\mathrm{MTF} = \frac{\mathrm{Imax - Imin}}{\mathrm{Imax + Imin}} \\ &\mathrm{Imax} = \text{maximum intensity} \\ &\mathrm{Imin} = \text{minimum intenstiy} \end{aligned}}$$

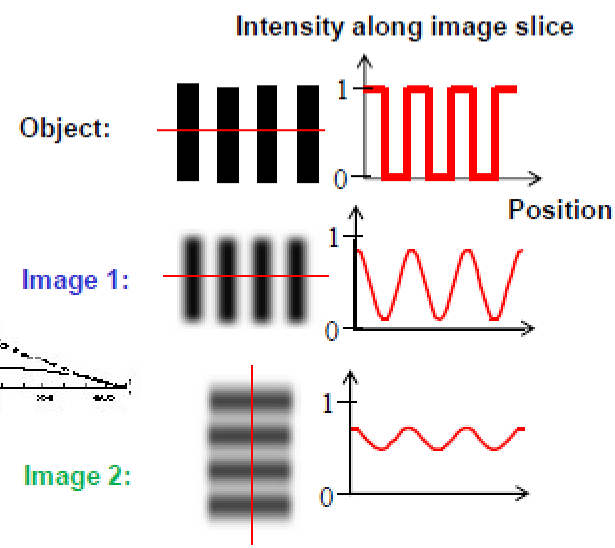
  - For object, contrast=1 (pure black and white)

MTF

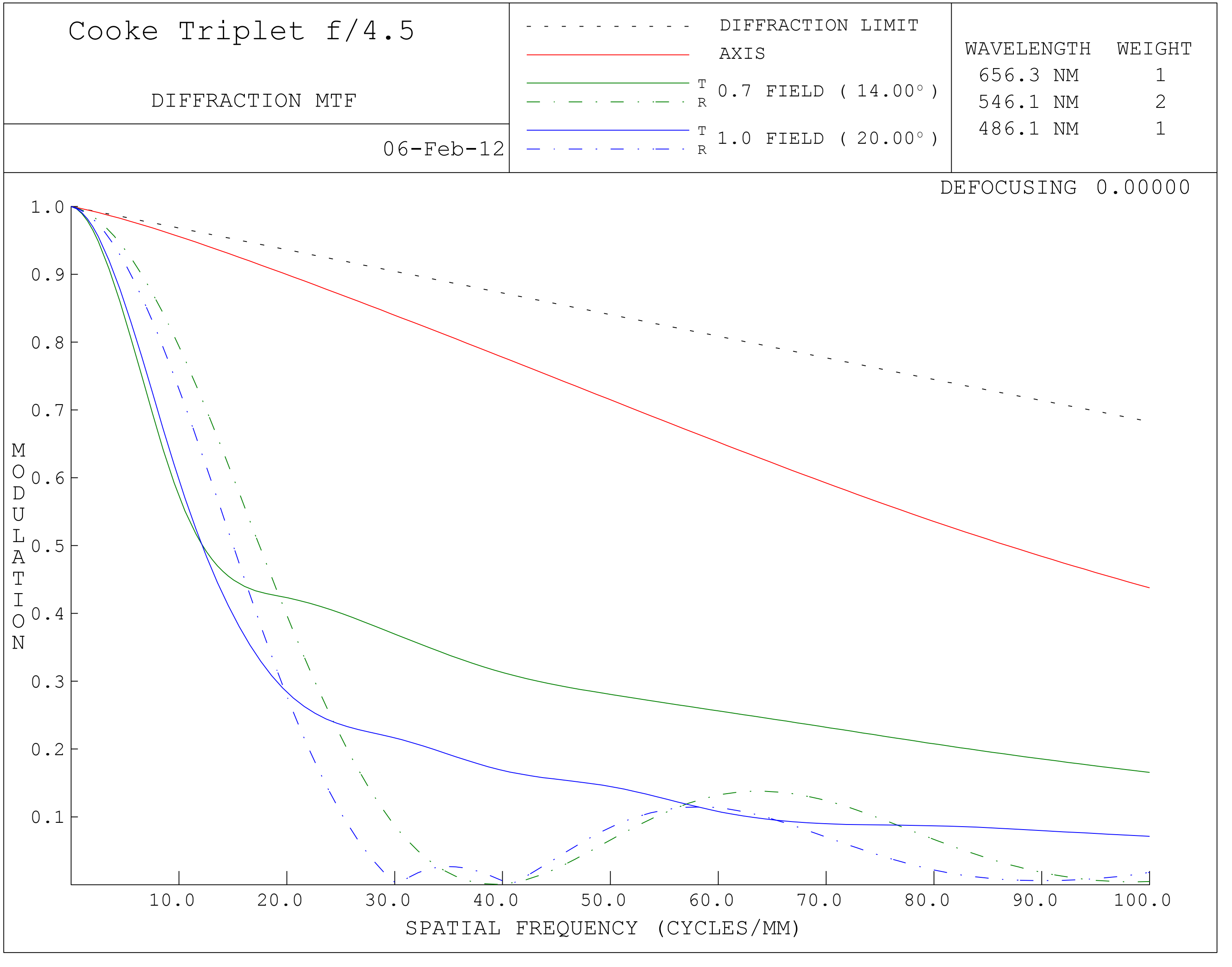
- MTF depends on target orientation(direction of variation of intensity) S=Sagittal(R=Radial) or T=Tangential







MTF vs. spatial frequency



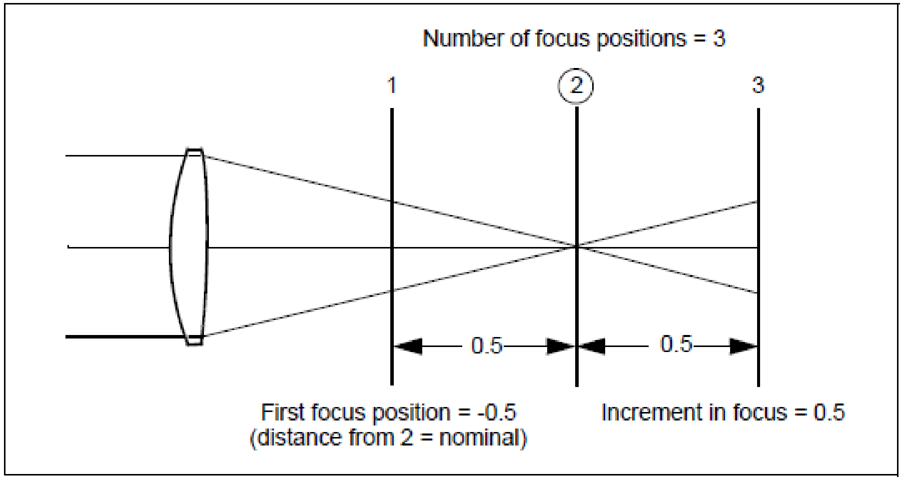
Through-focus analysis

- Can perform MTF (and other analyses) through-focus

- NFO num_of_focus_pos [....z]
  - Specifies number of focus positions

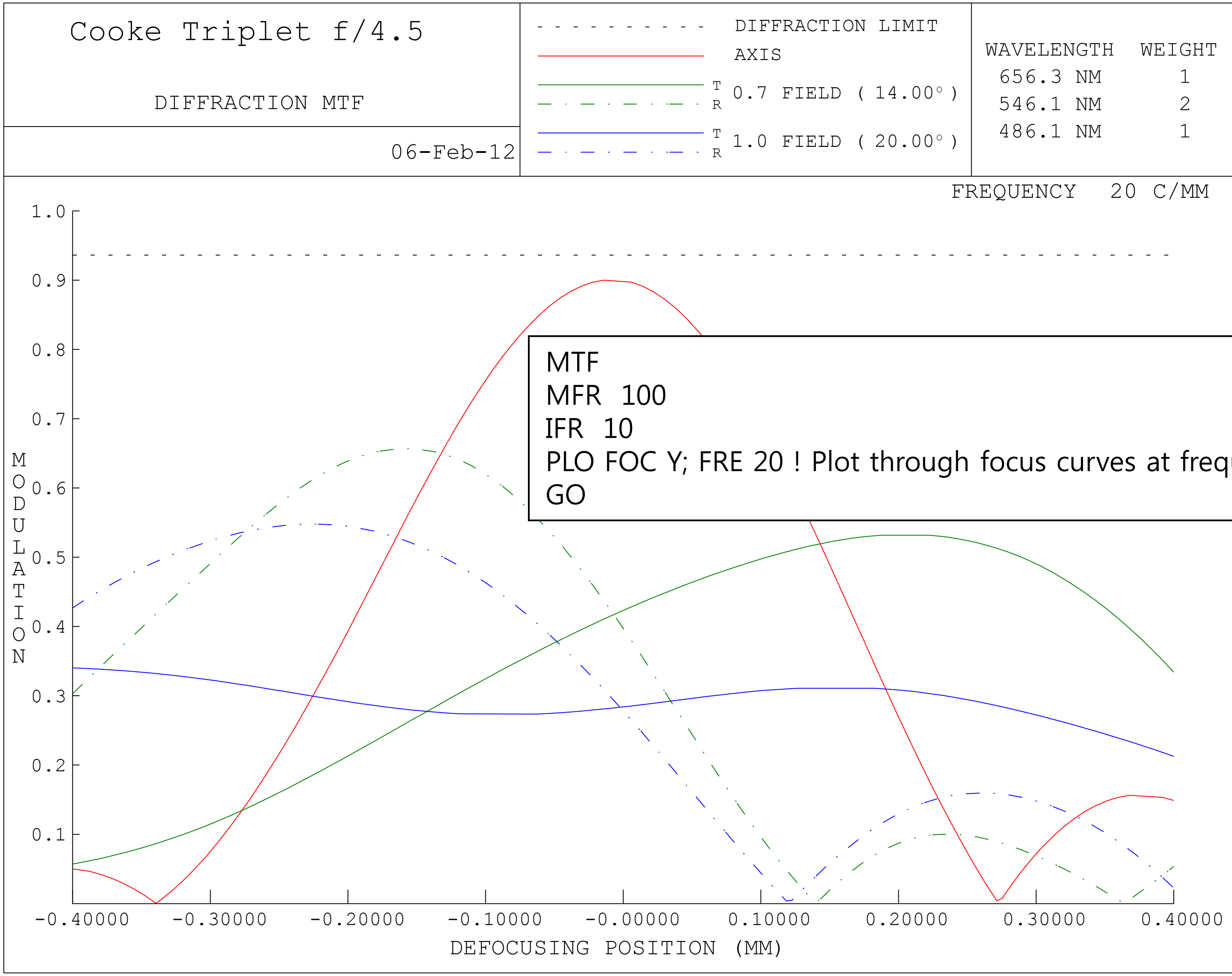
- FFO first_foc_pos [....z]
  - Specifies first focus positon

- IFO incr_in_focus [....z]
  - Specifies increment in focus position



NFO 3
FFO -0.5
IFO 0.5

Through-focus MTF (NFO 9;FFO -0.4;IFO 0.1)



MTF
MFR 100
IFR 10
PLO FOC Y; FRE 20 ! Plot through focus curves at frequency 20c/mm
GO

Section 6

Optical surfaces

Spherical surface

- Equation used

$$\boxed{z(r) = \frac{cr^2}{1+\sqrt{1-c^2r^2}} \qquad r^2 = x^2 + y^2}$$

c is vertex curvature (=1/radius)

$$x^2 + y^2 + (z - \frac{1}{c})^2 = \frac{1}{c^2}, \quad x^2 + y^2 \equiv r^2$$

$$(z - \frac{1}{c})^2 = \frac{1}{c^2}(1 - c^2r^2), \quad z = \frac{1}{c}(1 \pm \sqrt{1-c^2r^2})$$

$$z = \frac{1}{c}(1 - \sqrt{1-c^2r^2}), \quad \because z(0) = 0$$

$$z = \frac{1}{c}\frac{(1-\sqrt{1-c^2r^2})(1+\sqrt{1-c^2r^2})}{(1+\sqrt{1-c^2r^2})} = \frac{1}{c}\frac{(1-(1-c^2r^2))}{(1+\sqrt{1-c^2r^2})} = \frac{cr^2}{1+\sqrt{1-c^2r^2}}$$

Non-spherical surface types

- CODE V has many types of non-spherical surfaces
  - **CON** pure conic section (parabola, ellipse, hyperbola)
  - **ASP** 20^{th} order polynomial ashpere
  - **CYL** X or Y oriented cylinder
  - **XTO** X toroid (10^{th} order asphere rotated about x-axis)
  - **YTO** Y toroid (10^{th} order asphere rotated about y-axis)
  - AAS anamorphic asphere (differently aspheric in XZ and YZ planes)
  - **DIF GRT** linear diffraction grating on a 10^{th} order asphere
  - SPL spline surface (4 points)
  - THG thermal gradient (usually computed in ENV option)
  - **DIF DOE/HOE** holographic (diffractive) optical element
  - **MOD** lens module (perfect lens simulation)
  - SPS XXX family of additional special surfaces
  - UDS/UD2 user-defined surface (via FORTRAN or C subroutine)

Conic surface

- Equation used

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1+K)c^2 r^2}}$$

$$r^2 = x^2 + y^2$$

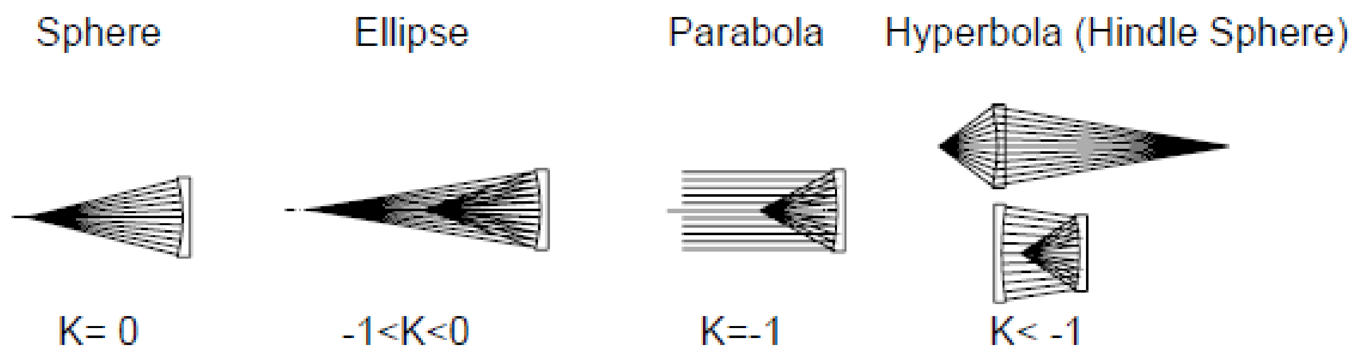
c is vertex curvature (=1/radius)

K is conic constant

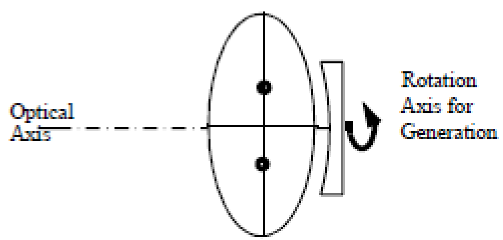
– Conic constant K (≠ e(eccentricity))
  - $K = 0$ sphere ($e = 0$)
  - $-1<K<0$ ellipse ($0 < e < 1$)
  - $K = -1$ parabola ($e = 1$)
  - $K < -1$ hyperbola ($e > 1$)
  - $K > 0$ oblate sphere (not a true conic section)

Conic surface

- Conic surfaces are most commonly seen in mirror systems

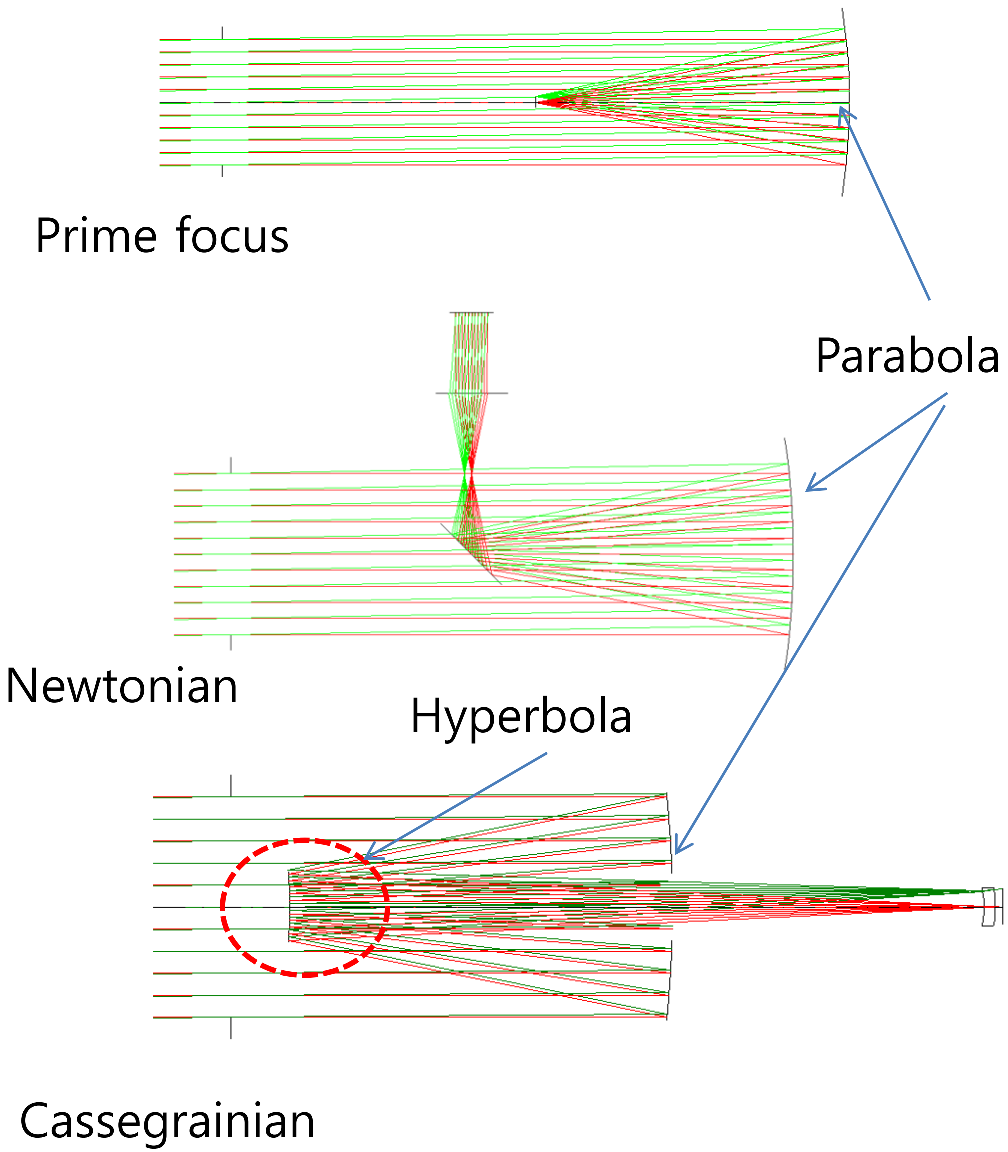


- Oblate sphere
  - Surface with positive conic constants K>0 are rarely seen, but when encountered should be treated with care



  - As an optical surface, an oblate sphere is not a conic and does not image point to point , even at the foci

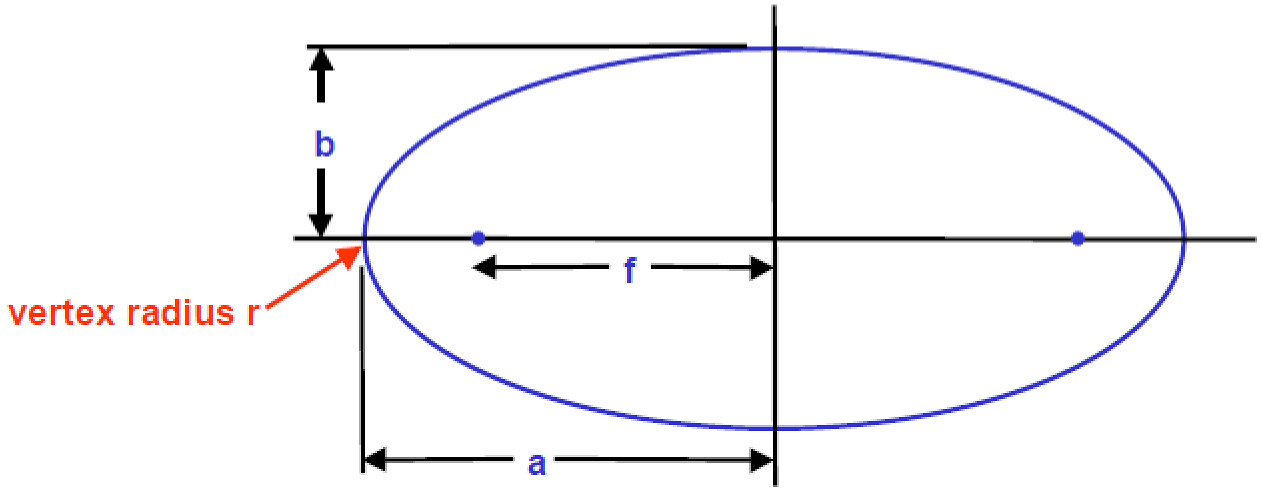
Reflecting telescope and antenna



A parabolic satellite communications antenna in German
http://en.wikipedia.org/wiki/File:Erdfunkstelle_Raisting_2.jpg

Elliptical surface

- Defined by semi-major axis a and semi-minor axis b and two foci



vertex radius	$r=b^2/a$
conic constant	$K=(b^2-a^2)/a^2$
center distance to foci	$f=(a^2-b^2)^{1/2}$
vertex distance to foci	$a \pm f$
semi-major axis	$a=r/(K+1)$
semi-minor axis	$b=r/(K+1)^{1/2}$

General aspheric surface

- Equation used

$$z(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + Ar^4 + Br^6 + Cr^8 + Dr^{10} + Er^{12} + Fr^{14} + Gr^{16} + Hr^{18} + Jr^{20}$$

$$r^2 = x^2 + y^2$$

c is vertex curvature (=1/radius)

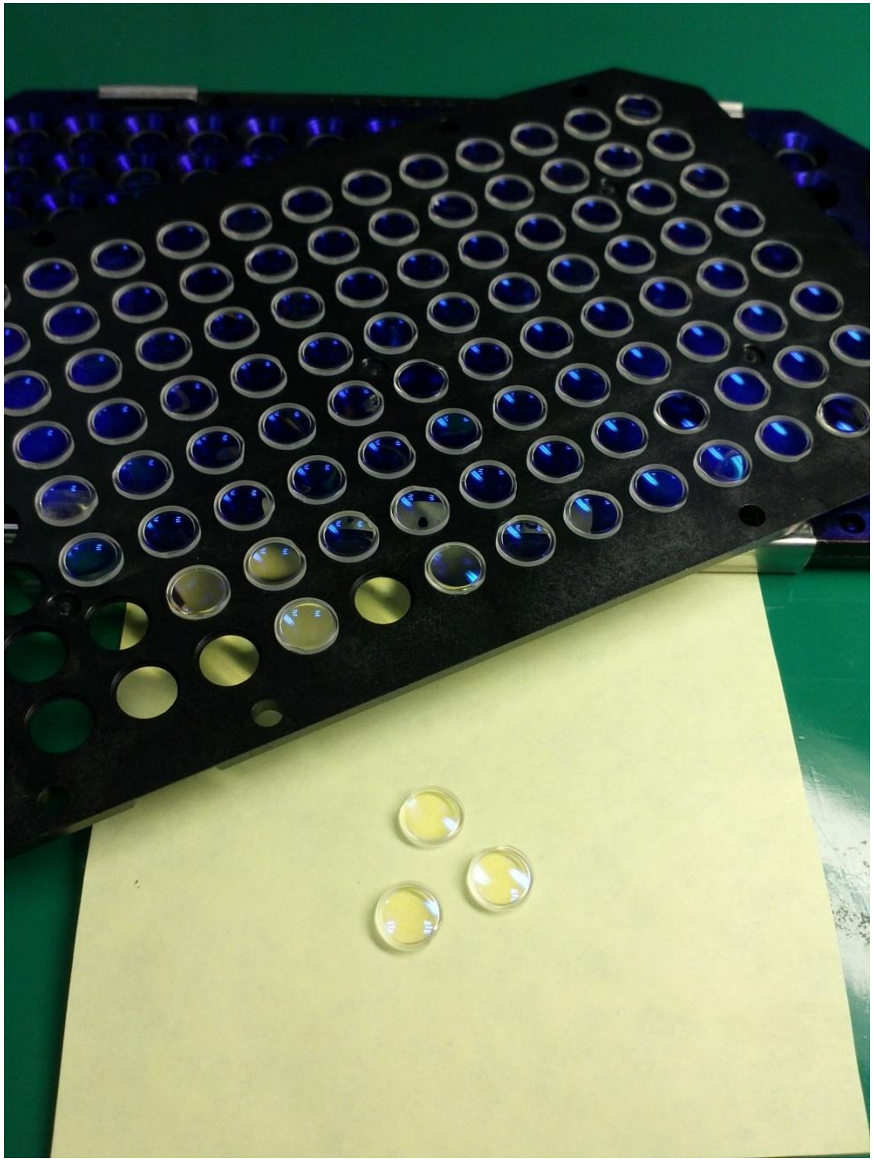
k is conic constant

A, B, C, D, E, F, G, H, J are aspheric deformation coefficients

Section 7

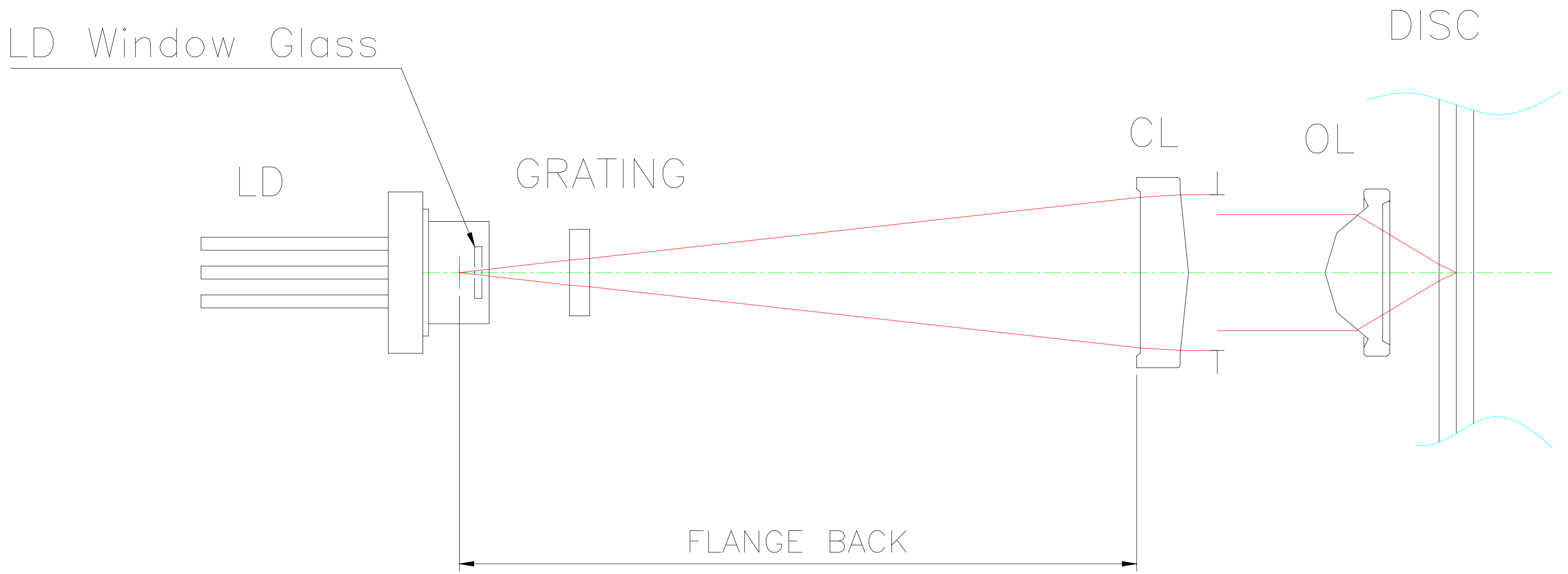
Making your first lens

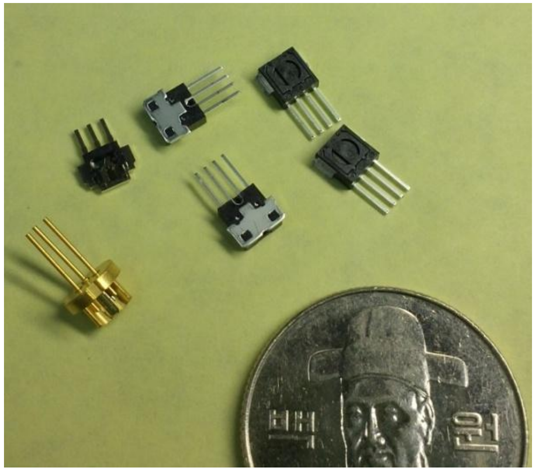
Laser collimator lens



Target

- Typical layout



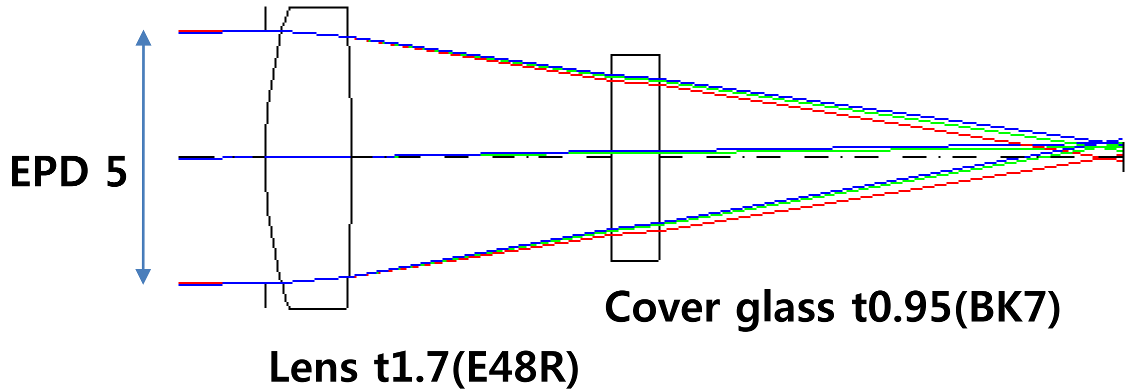


Specification

- Purpose : Collimator lens for DVD Player
- Wavelength : 650nm
- Focal length : 20mm
- Numerical aperture : 0.125
- Magnification : 0
- Flange back : 19.17mm(Cover Glass 포함)
- Distance from lens vertex to flange : 0.15
- Lens thickness : 1.7mm
- Cover glass : 0.95mm (BK7)
- Material : ZEONEX E48R
- Surface Type
  - 1st Surface : Conic surface
  - 2nd Surface : Spherical surface
- Design temperature : 25°C
- Image height : 0.3mm
- Diameter : 6.6mm

Layout for design

- Use EPD instead of NA(or NAO)

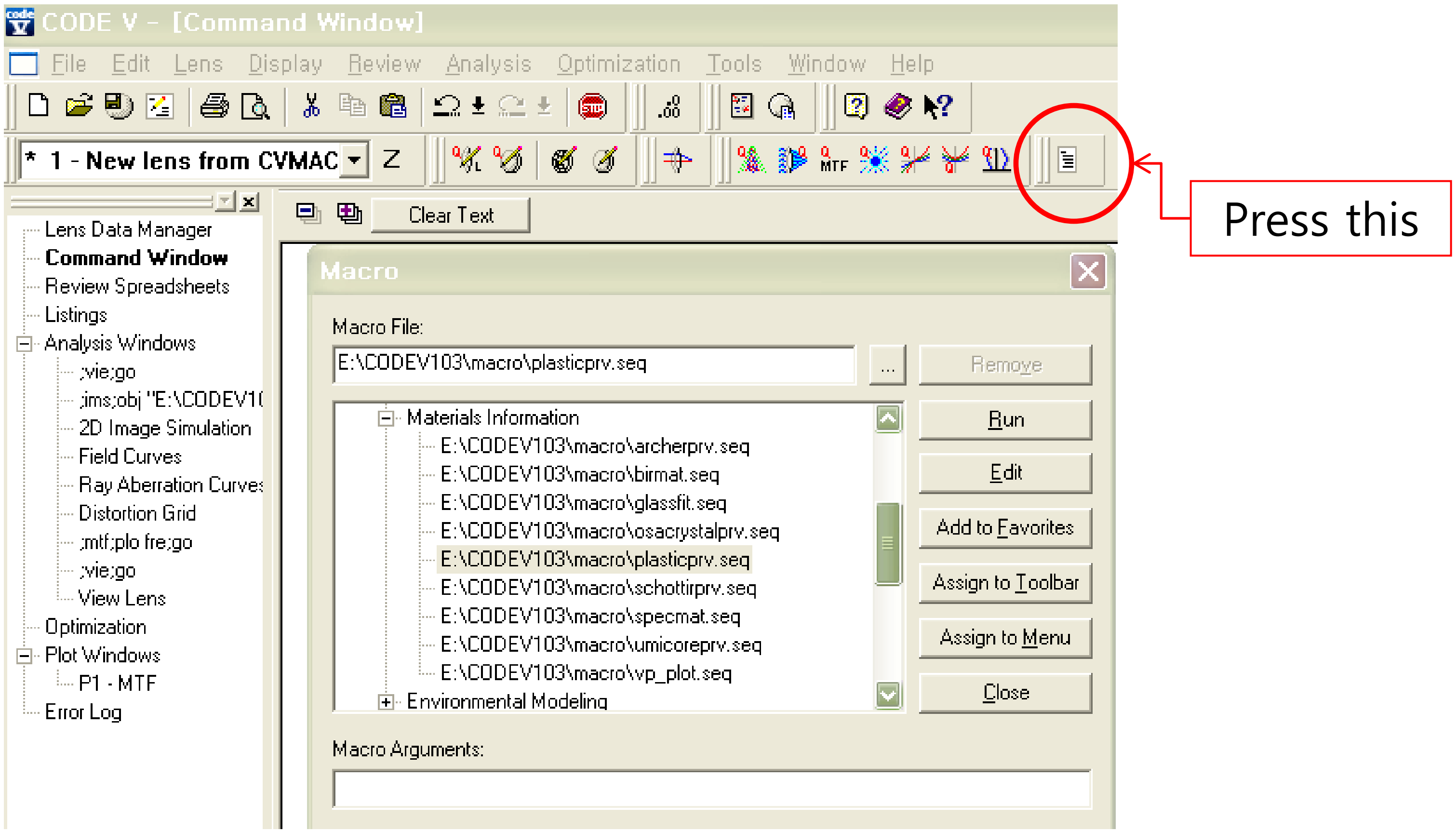


  - EPD(Entrance pupil diameter)=2 X f X NA

    LEN NEW
    EPD 5
    WL 650
    YIM 0 0.21 0.3

Plastic material

- There are some plastic material data in plasticprv.seq
- IN cv_macro:plasticprv or choose it from window button

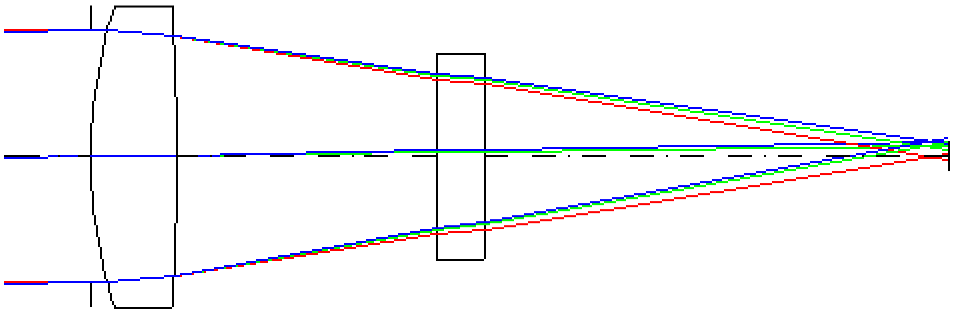


'Z-330R'	ZEONEX - Grade 330R	[5]	1600 - 400 nm	25	0.95	900	-	509.559
'Z-480R'	ZEONEX - Grade 480R	[5]	1600 - 400 nm	25	1.01	600	-	525.562
'Z-E48R'	ZEONEX - Grade E48R	[5]	1600 - 400 nm	25	1.01	600	-	530.558

Surface data

- Now surface pointer is at the stop surface

```
S 10 1.7 'Z-E48R'      ! RDY 10 for initial value
S -50 0.15             ! RDY -50 for initial value
                       ! Distance(0.15) from lens vertex to flange
S 0 5
S 0 0.95 BK7           ! Cover glass
S 0 0
PIM                    ! Solver for first order layout

TOW;VIE;GO             ! Drawing lens
```



First order data

CODE V> FIR

INFINITE CONJUGATES

EFL	15.9218 ← Target : 20mm How?
BFL	9.2086
FFL	-15.7346
FNO	3.1844

CODE V> IND

REFRACTIVE INDICES

GLASS CODE	650.00
'Z-E48R'	1.528571
BK7_SCHOTT	1.514520

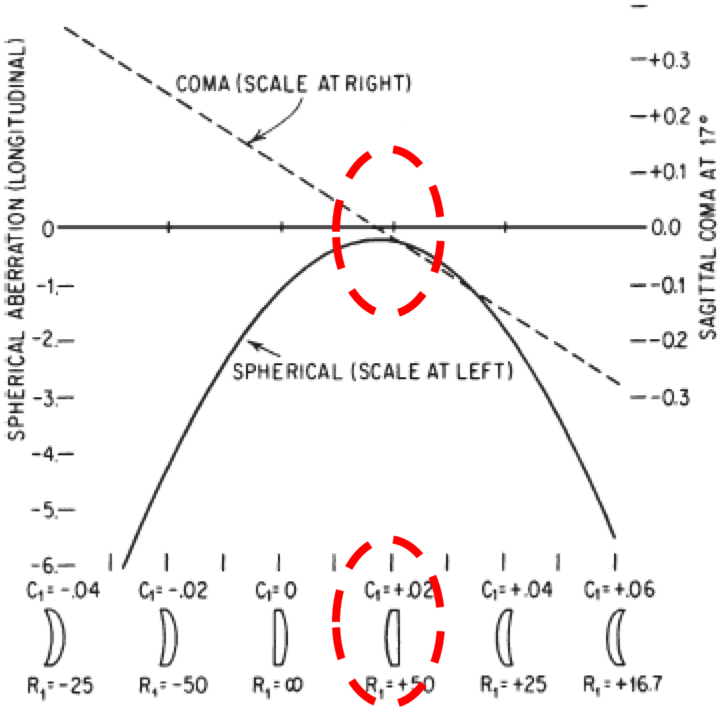
Lens shape

- Thick lens formula

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right]$$

- n(refractive index) and thickness d were fixed

- therefore we must change R1 and R2, but there are many possible solutions



From MOE, Smith

Spherical aberration and coma as a function of lens shape. Data plotted are for a 100mm focal length at f/10 covering ±17° field

EFL optimization

CODE V> CCY S2 0; CCY S3 0 ! Making R1 and R2 variable

CODE V> SUR S2..3 F

		RDY	THI	RMD	GLA	CCY	THC	GLC
	2:	10.00000	1.700000		'Z-E48R'	0	100	
>	3:	-50.00000	0.150000			0	100	

CODE V> AUT;EFL=20;GO ! Optimization

CODE V> SUR S2..3

		RDY	THI	RMD	GLA
	2:	12.14842	1.700000		'Z-E48R'
>	3:	-77.49628	0.150000		

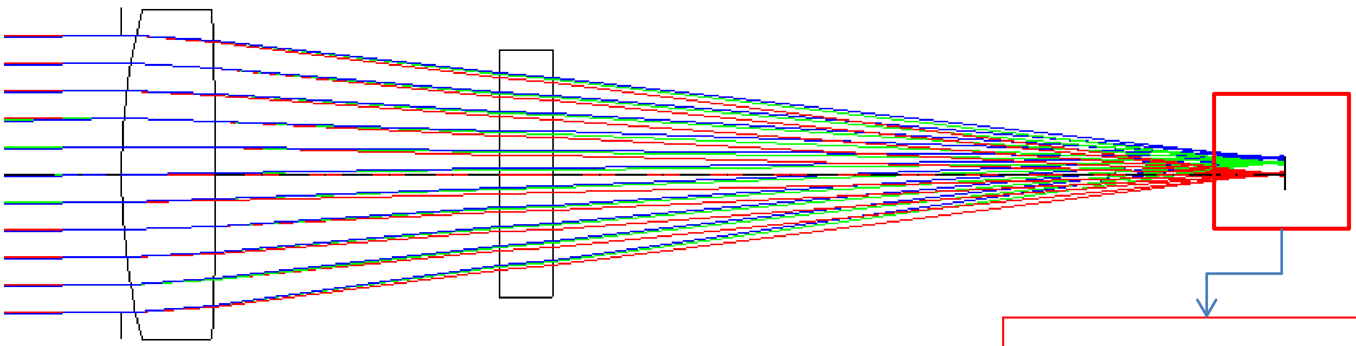
CODE V> FIR

INFINITE CONJUGATES

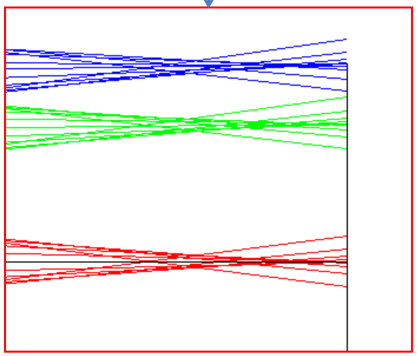
EFL	20.0000	← meet target, but...
BFL	13.2550	
FFL	-19.8483	
FNO	4.0000	

Review lens

TOW;VIE;GO

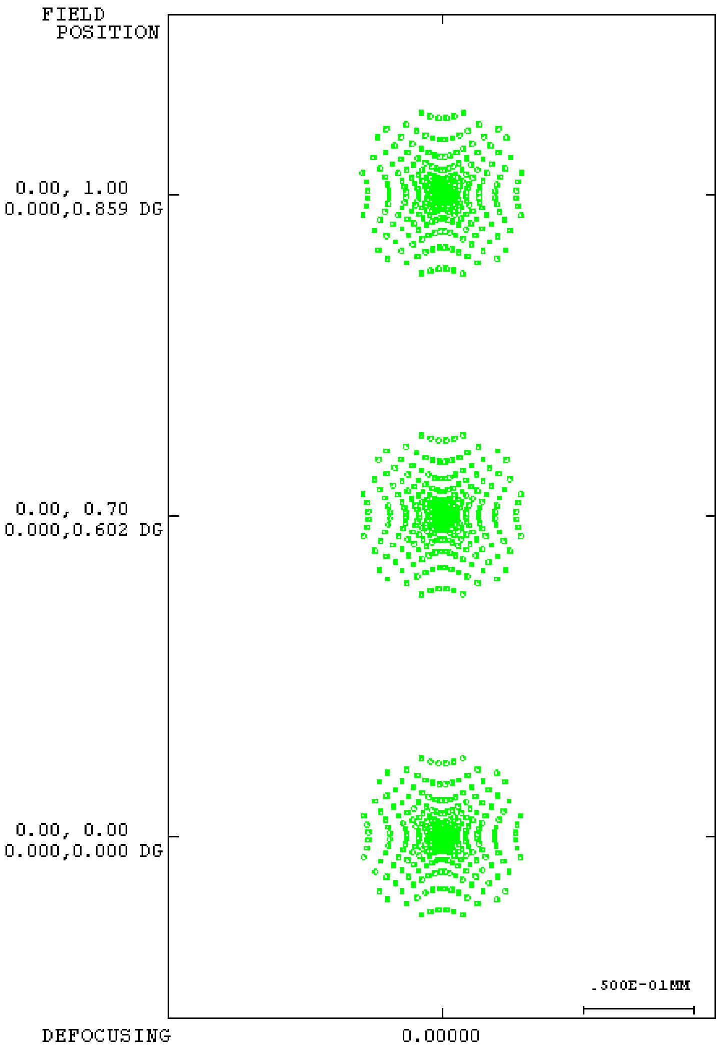


Under corrected
spherical aberration

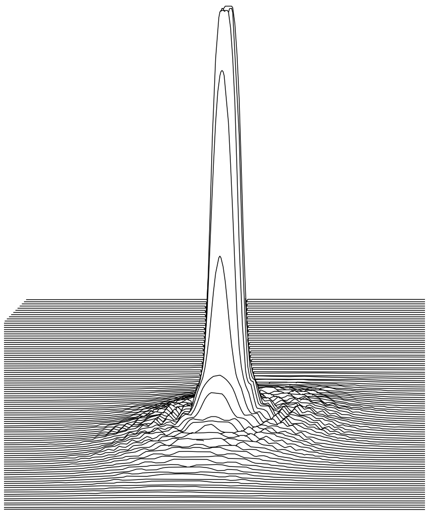


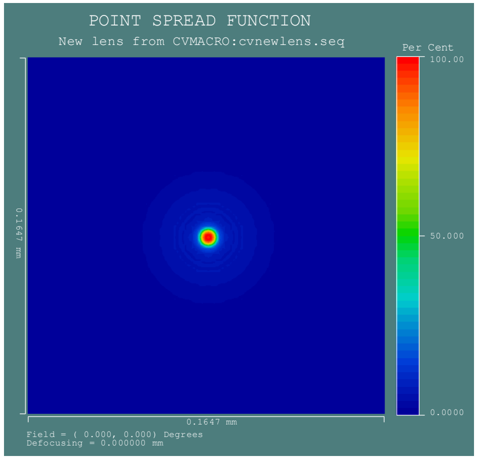
Spot size and PSF

SPO;SSI 0.05;GO



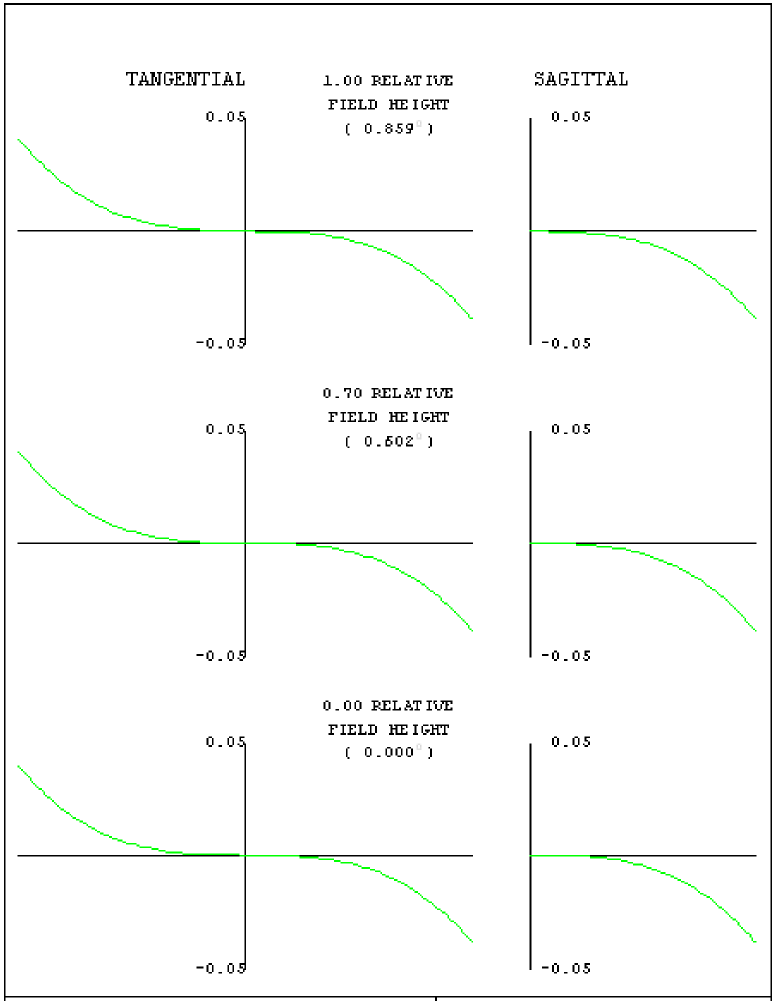
PSF;LIS NO;DIS YES;GO



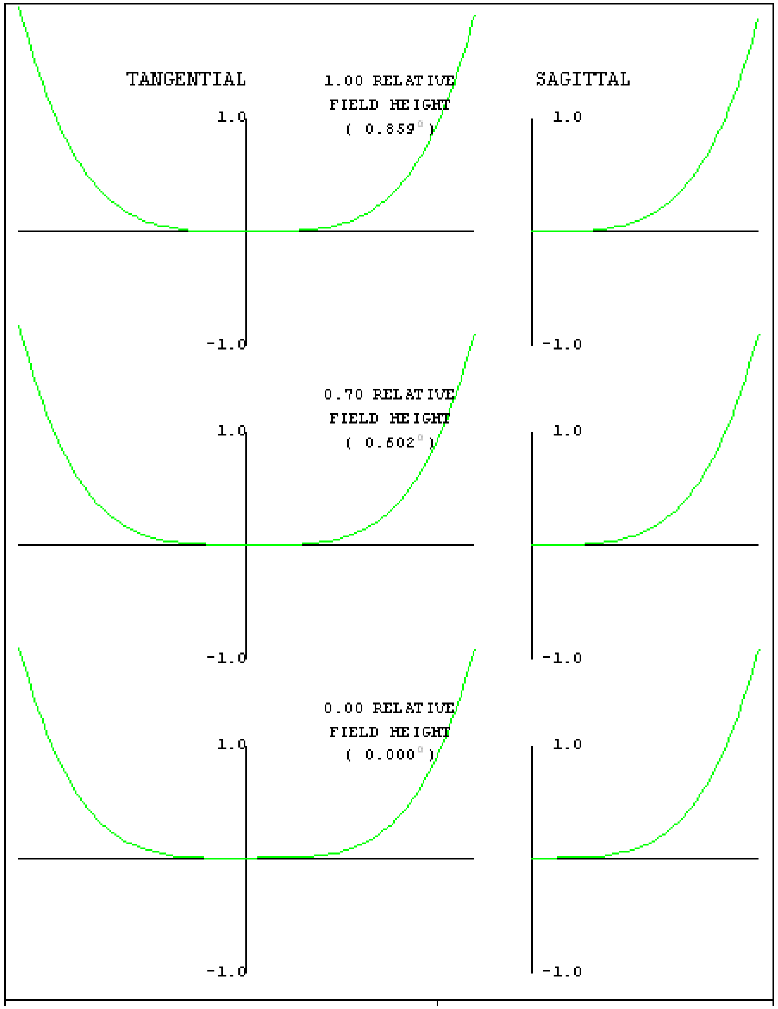


Ray aberration curve

RIM;GO

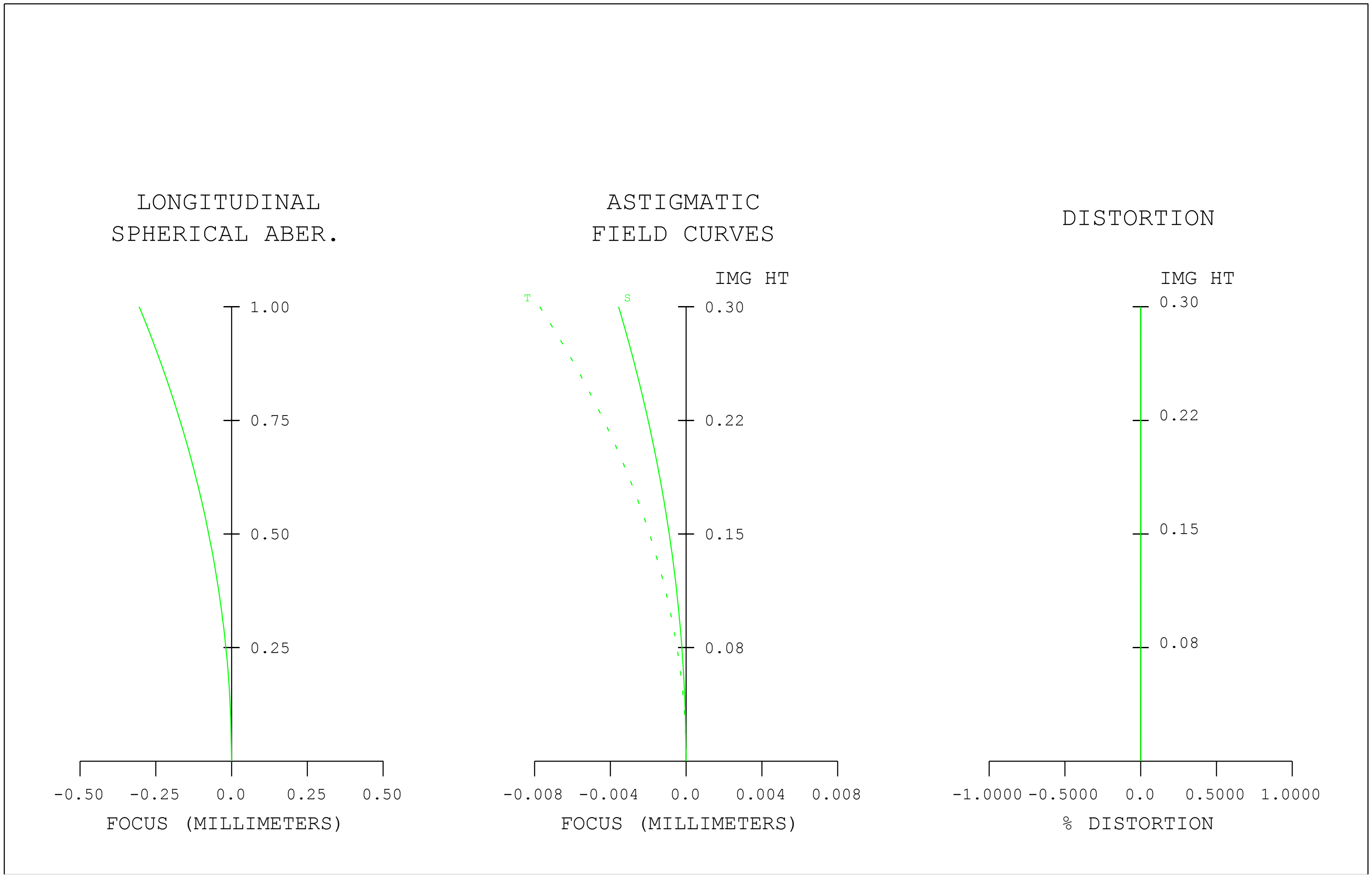


RIM;WFR YES;GO !OPD



Field curves

FIE;ZFO YES;LSA 0.5;FFD NO;GO



Wavefront error

WAV;GO

X REL. FIELD	0.00	0.00	0.00
Y REL. FIELD	0.00	0.70	1.00
WEIGHTS	1.00	1.00	1.00
NUMBER OF RAYS	316	316	316

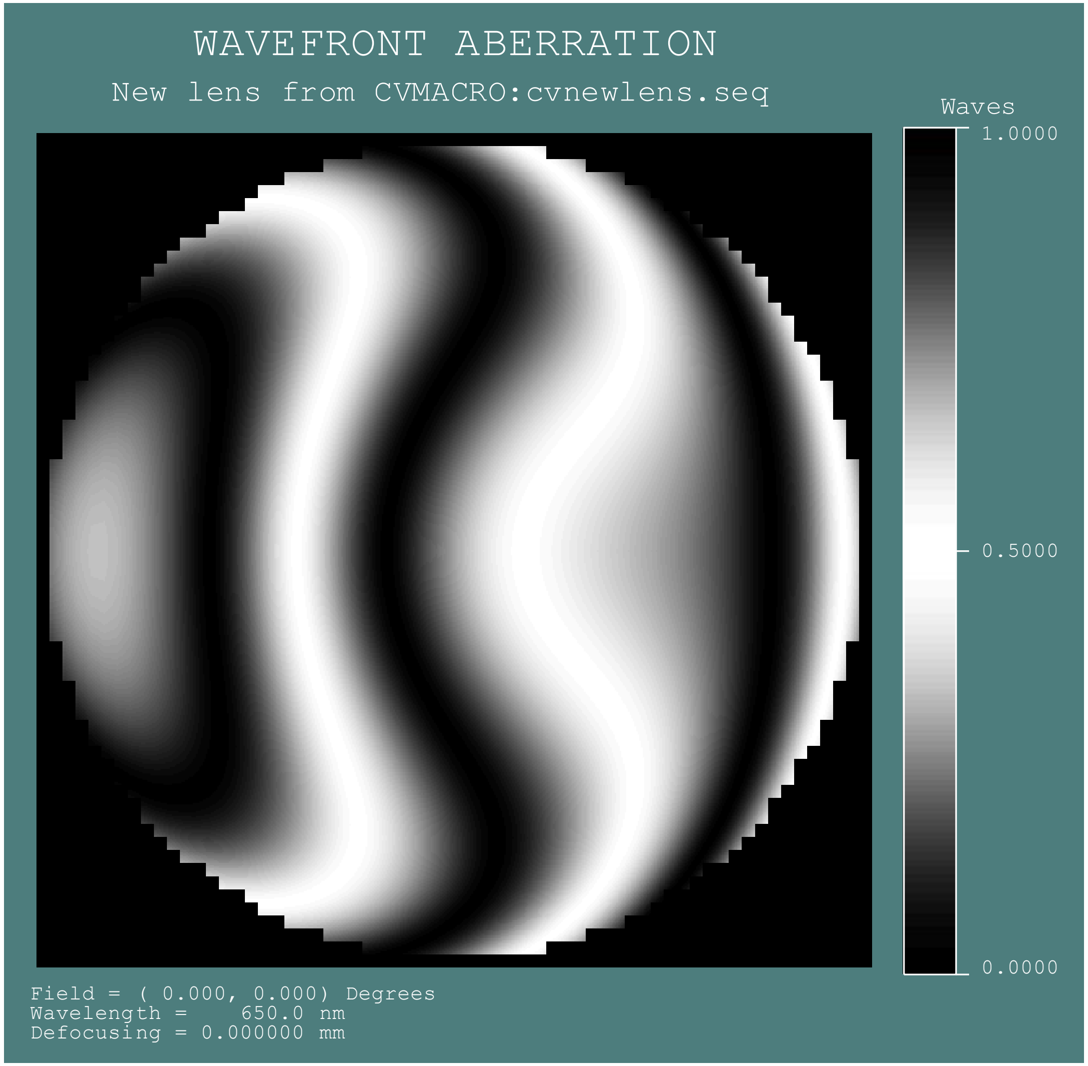
WAVELENGTHS	650.0
WEIGHTS	1

FIELD			BEST INDIVIDUAL FOCUS				BEST COMPOSITE FOCUS			
	FRACT	DEG	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL
X	0.00	0.00	0.000000	-0.153572	0.1413	0.455	0.000000	-0.156371	0.1417	0.453
Y	0.00	0.00	0.000000				0.000000			
X	0.00	0.00	0.000000	-0.156332	0.1415	0.454	0.000000	-0.156371	0.1415	0.454
Y	0.70	0.60	0.000123				0.000123			
X	0.00	0.00	0.000000	-0.159204	0.1419	0.452	0.000000	-0.156371	0.1423	0.450
Y	1.00	0.86	0.000134				0.000176			

COMPOSITE RMS FOR
POSITION 1: 0.14182

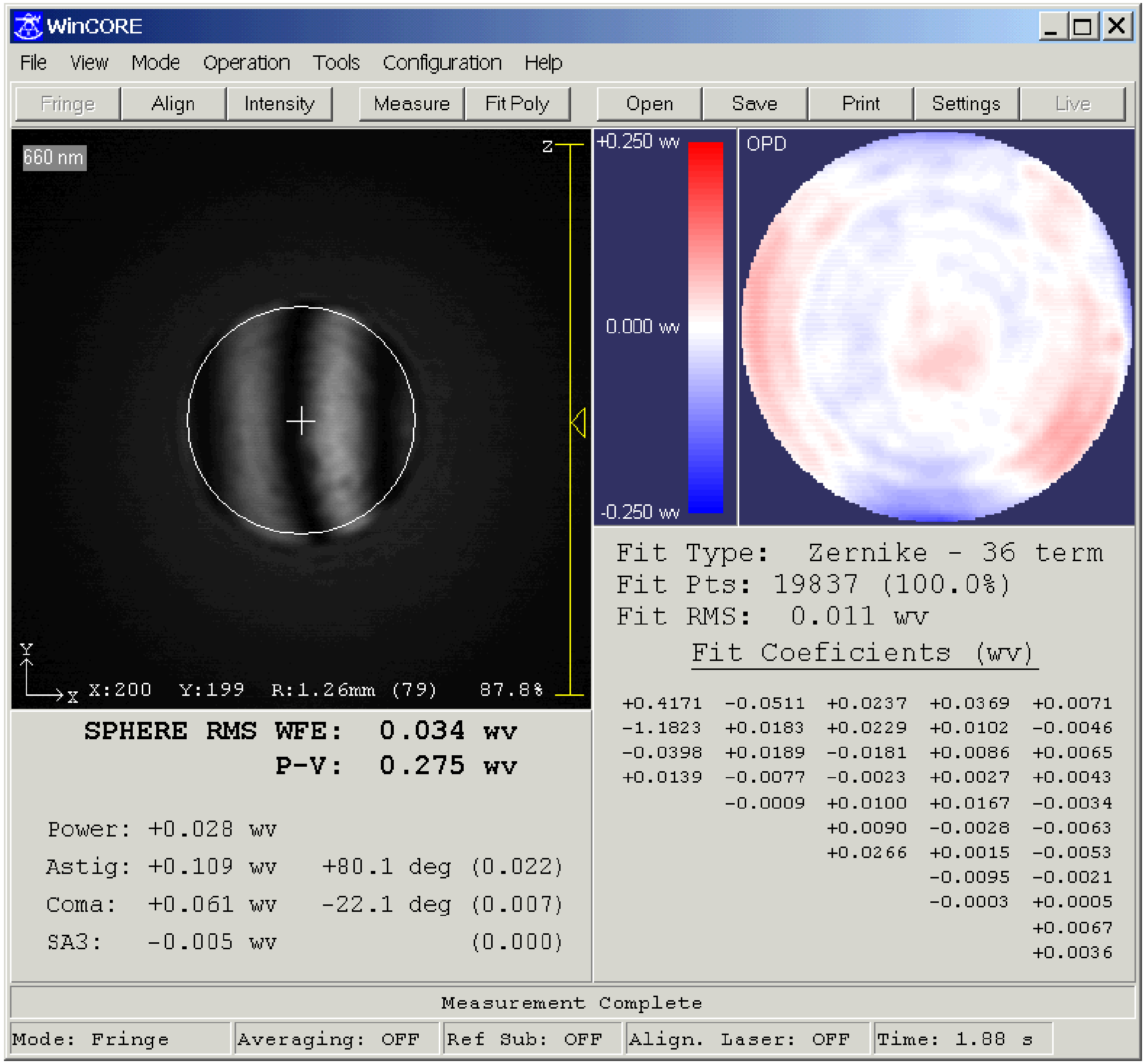
Wavefront aberration seen from interferometer

PMA;ADW FOC 1.5 0 0 0;LIS NO;DIS INT YES;RAN COL RGB 1 1 1;GO



Example

- DVD optical pickup wavefront error by SEXTANT interferometer



Making performance better

CODE V>CON S2 ; KC 0

CODE V>AUT;EFL=20;GO ! Only run once

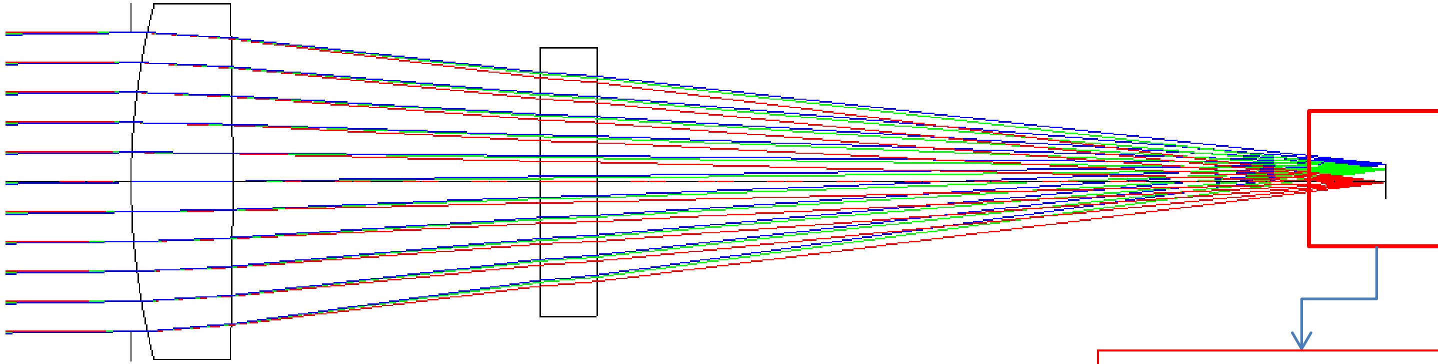
```
CYCLE NUMBER 4:
 ERR. F.  =      0.03658313     (change =      -0.00000008)   ← That's enough
  X     0.01293874     0.00274143     0.00610156
  Y     0.01293874     0.00755392     0.06747499
    Normal AUTO Completion - System improvement less than IMP
```

CODE V>SUR S2..3

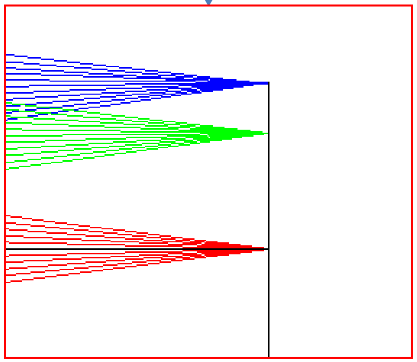
```
              RDY           THI          RMD        GLA
>   2:       11.66411      1.700000                 'Z-E48R'
      CON:
      K  :   -0.737208
    3:      -107.15905      0.000000
```

Review lens

TOW;VIE;GO

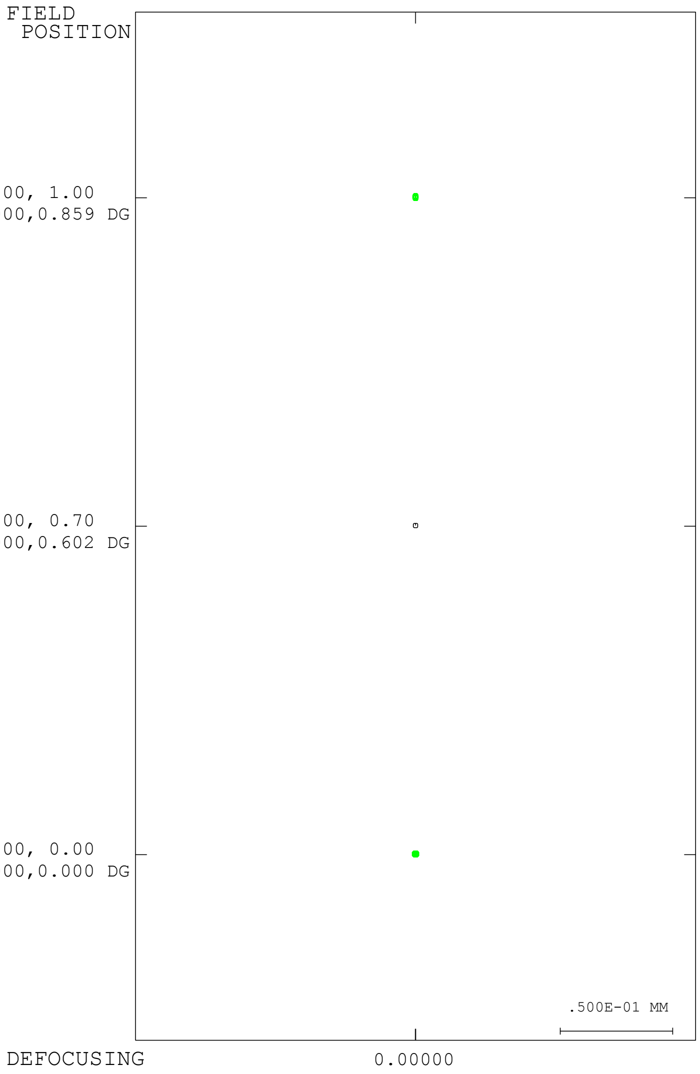


Perfect coincidence

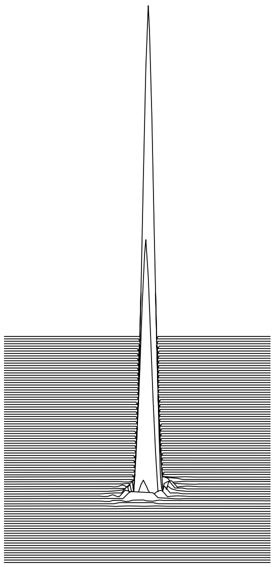


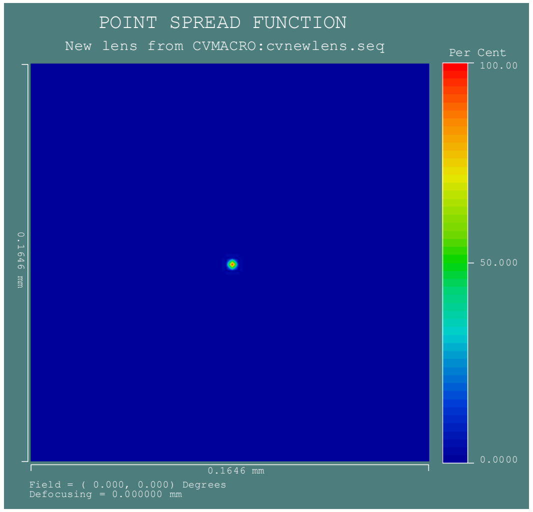
Spot size and PSF

SPO;SSI 0.05;GO



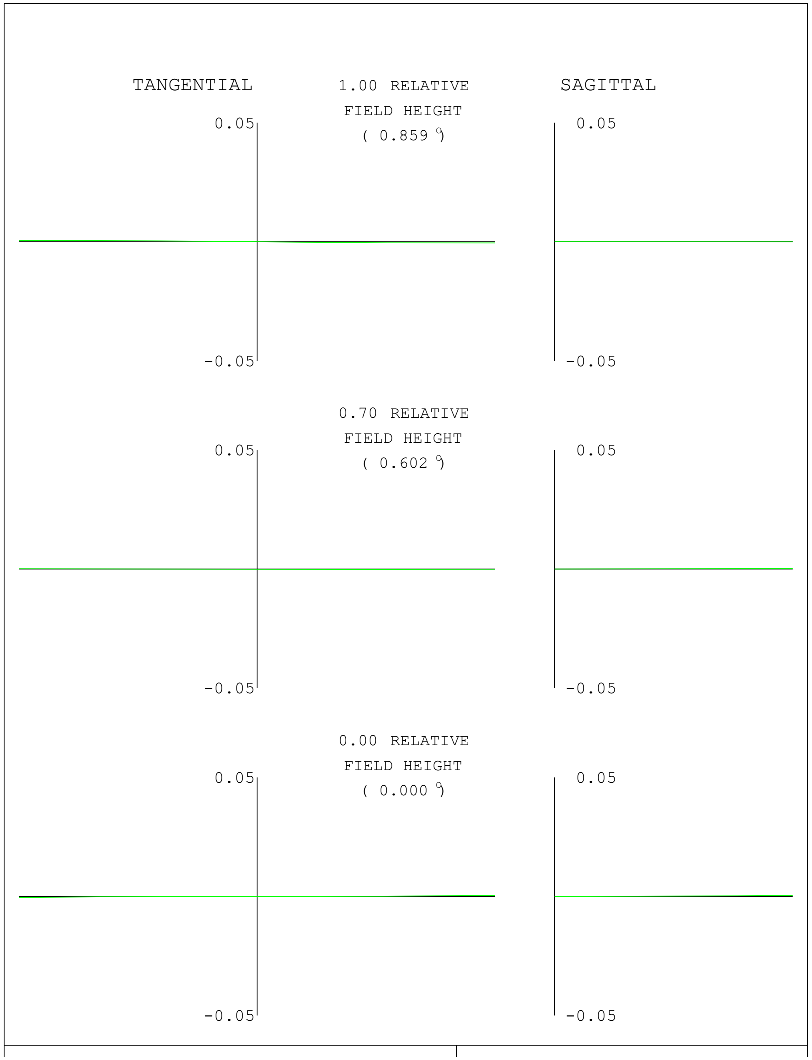
PSF;LIS NO;DIS YES;GO



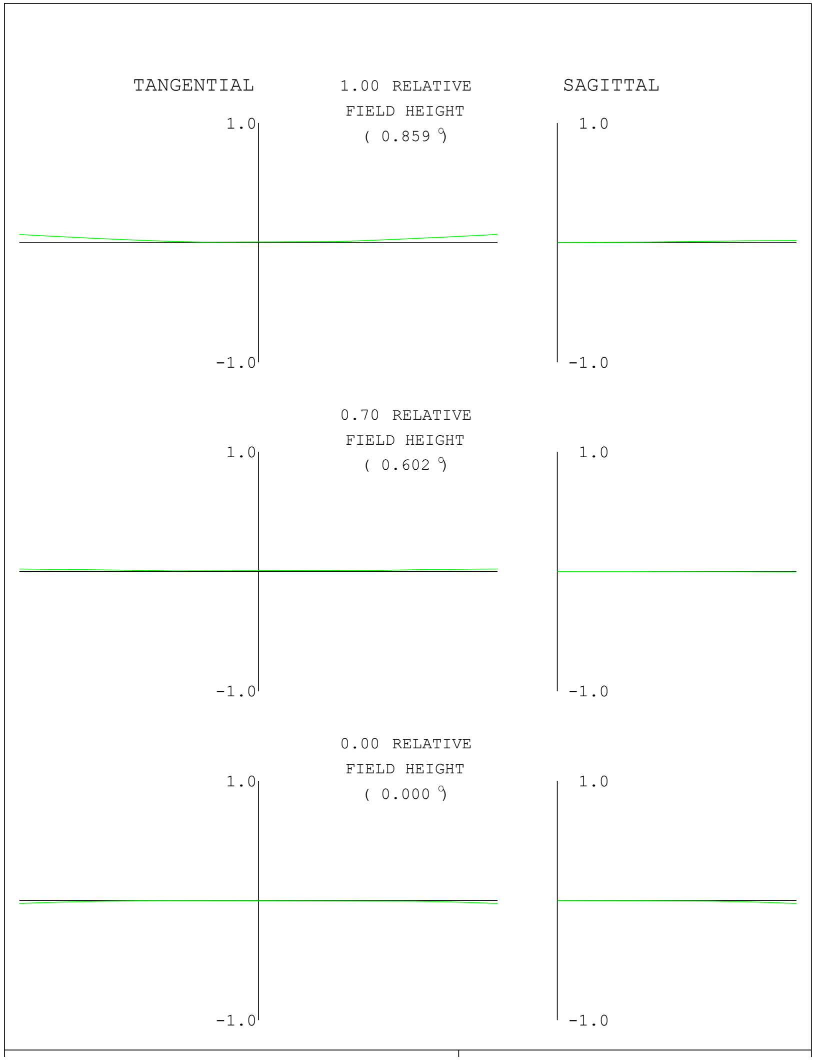


Ray aberration curve

RIM;GO

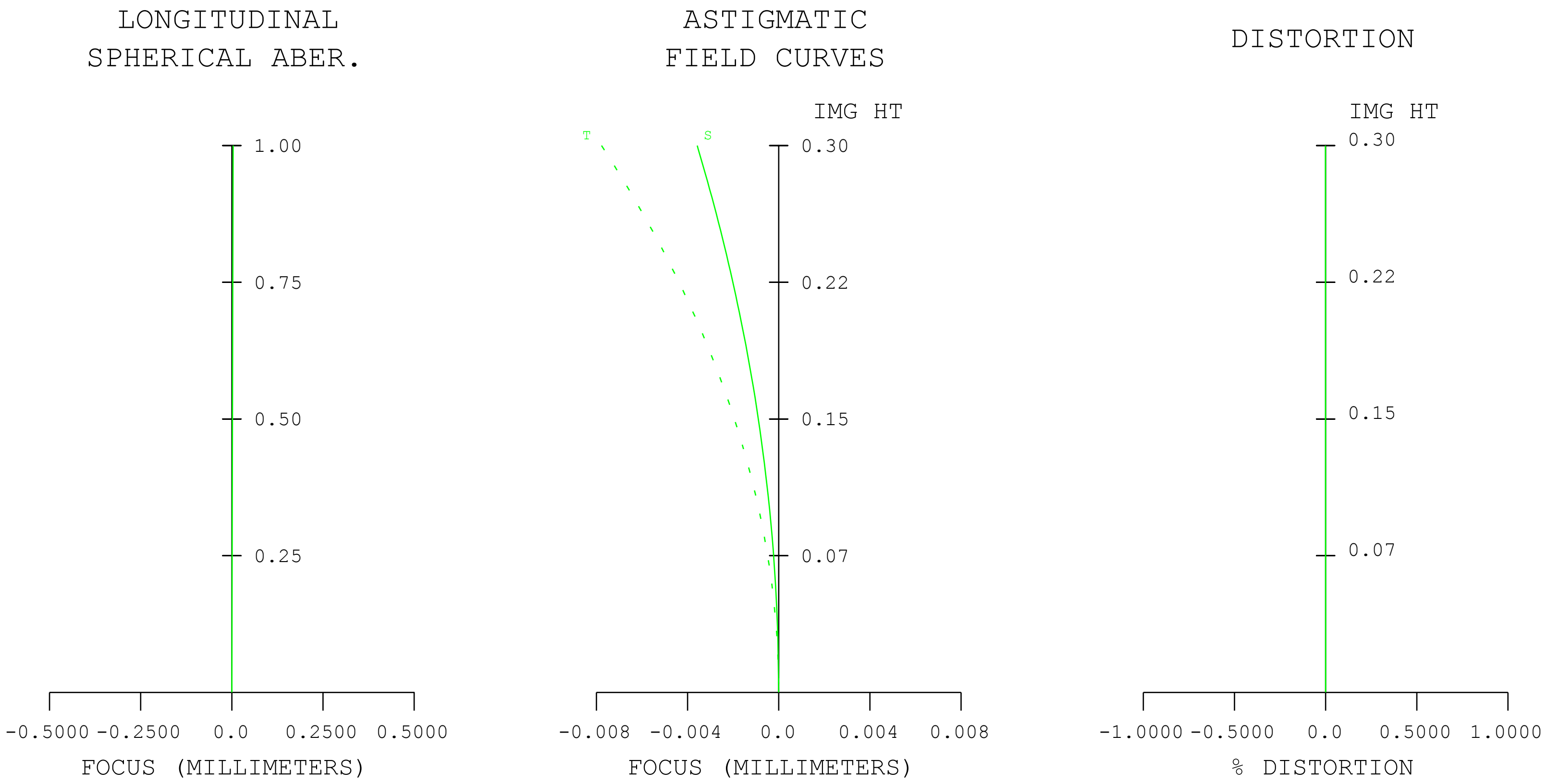


RIM;WFR YES;GO !OPD



Field curves

FIE;ZFO YES;LSA 0.5;FFD NO;GO



Wavefront error

WAV;GO

X REL. FIELD	0.00	0.00	0.00
Y REL. FIELD	0.00	0.70	1.00
WEIGHTS	1.00	1.00	1.00
NUMBER OF RAYS	316	316	316

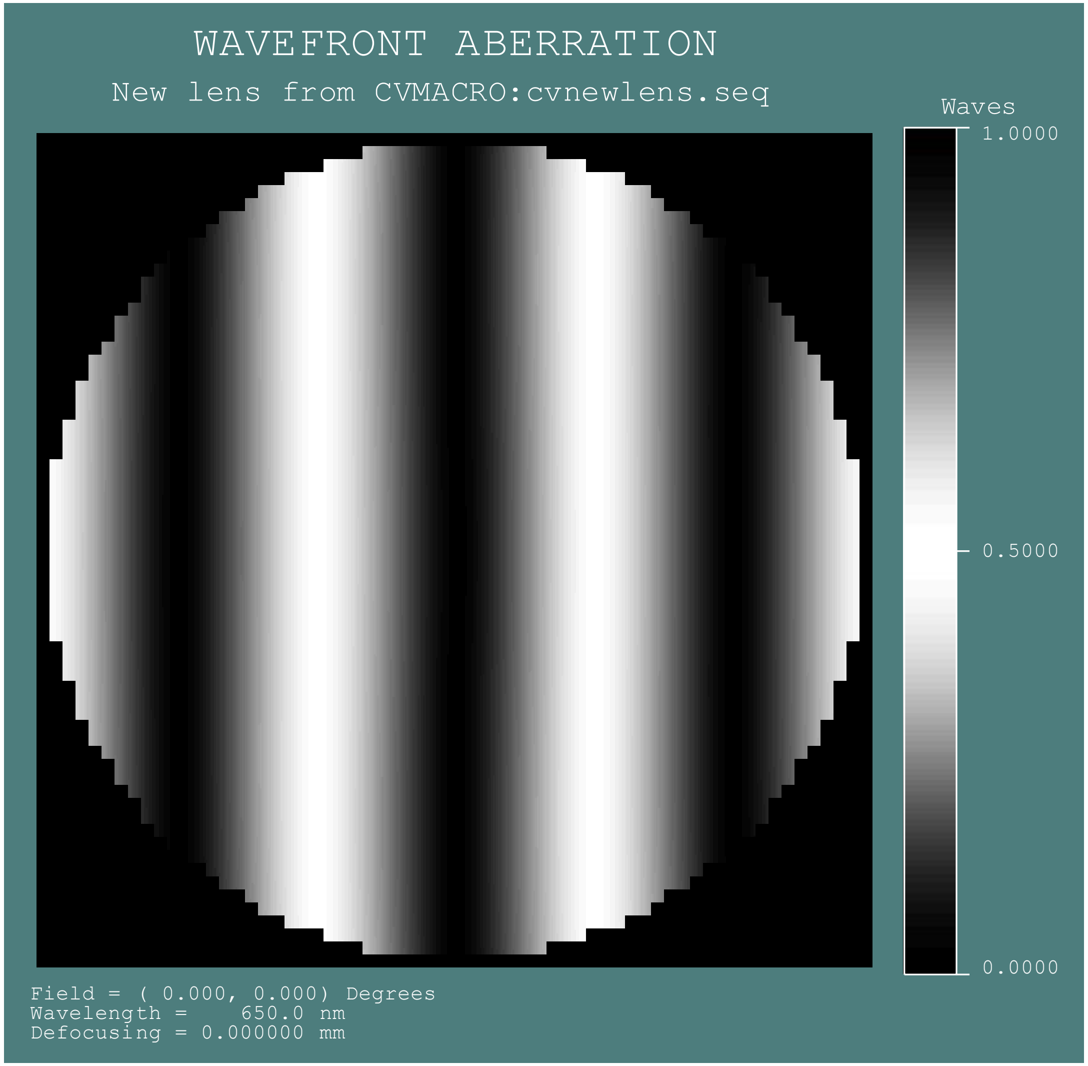
WAVELENGTHS	650.0
WEIGHTS	1

FIELD			BEST INDIVIDUAL FOCUS				BEST COMPOSITE FOCUS			
	FRACT	DEG	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL
X	0.00	0.00	0.000000	0.002166	0.0016	1.000	0.000000	-0.000670	0.0101	0.996
Y	0.00	0.00	0.000000				0.000000			
X	0.00	0.00	0.000000	-0.000630	0.0054	0.999	0.000000	-0.000670	0.0054	0.999
Y	0.70	0.60	-0.000002				-0.000003			
X	0.00	0.00	0.000000	-0.003540	0.0106	0.996	0.000000	-0.000670	0.0146	0.992
Y	1.00	0.86	-0.000046				-0.000003			

COMPOSITE RMS FOR
POSITION 1: 0.01073

Wavefront aberration seen from interferometer

PMA;ADW FOC 1.5 0 0 0;LIS NO;DIS INT YES;RAN COL RGB 1 1 1;GO



Save lens

- SAV CL_20mm ! CL_20mm.len
- SAV ! save CL_20mm.len and old version
  ! become CL_20mm.1.len

- WRL CL_20mm ! CL_20mm.seq

Saving the environment

- The set of windows and formats that you are using with a lens file is called the “environment”

- If you use **File>Save Lens As** to save a lens file called abc.len, the program also saves a file called abc.env in the same directory as abc.len

- This “environment file” records all the non-lens information, and if you later use **File>Open** to restore the lens, the saved windows are restored as well
  - Note : this will also close all analysis windows that are open

- If you use the Command Window to save and open lens files (SAV abc.len, RES abc.len), the environment file is not created or updated (on SAV) and is not restored even if it exists (on RES)

2nd day

Section 8

Analysis II

Analysis

- Pupil map (PMA)
- Spot diagram (SPO)
- Point spread function (PSF)
- Wavefront analysis (WAV)
- 2D image simulation (IMS)

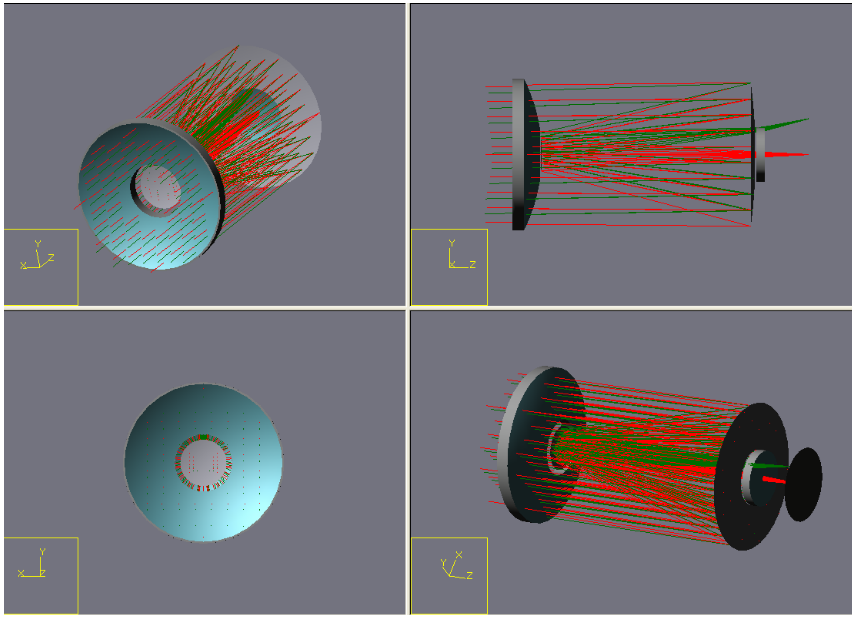
Pupil map

- Main output is a list and optional plot of the OPD across the (exit) pupil
  - Separate outputs for each wavelength, field, and zoom position
  - Also lists the RMS wavefront error of the OPD data and the RMS after removing tilt and after removing tilt and focus error

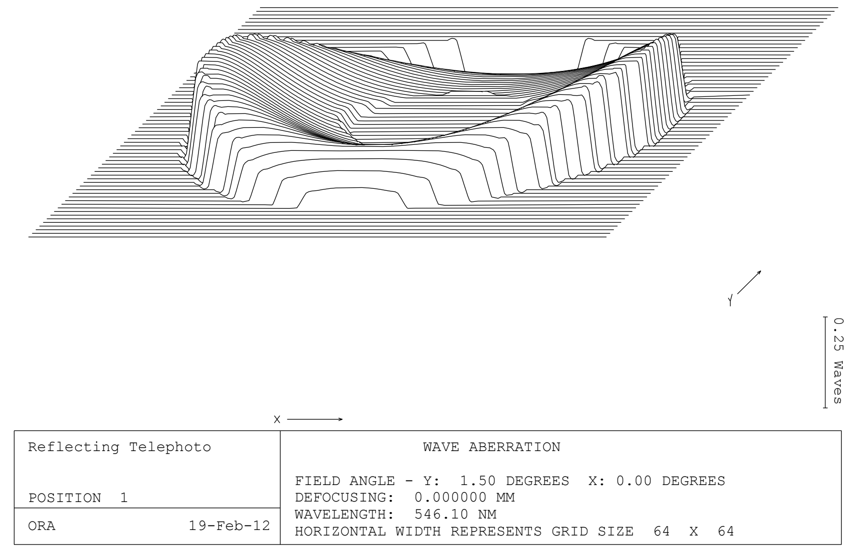
- OPD data can be converted to Zernike polynomials and can be saved as interferograms

- Alternative outputs instead of OPD
  - Pupil intensity
  - Polarization phase
  - Ray clipping map

PMA outputs (1)



Maksutov(1896 - 1964) telescope

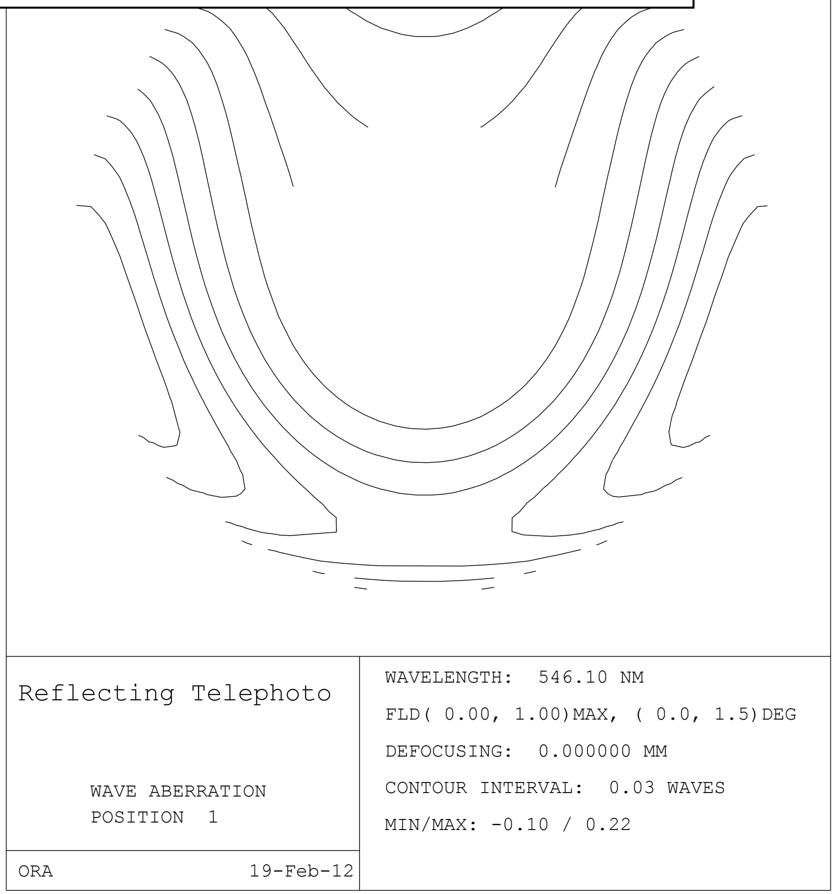


Perspective plot @f2

RES CV_LENS:MAKSUTOV
PMA
TGR 64
NRD 50 ! Number of rays across pupil diameter
SSI 0.25 ! Scale factor : one quarter wave/scale bar
GO

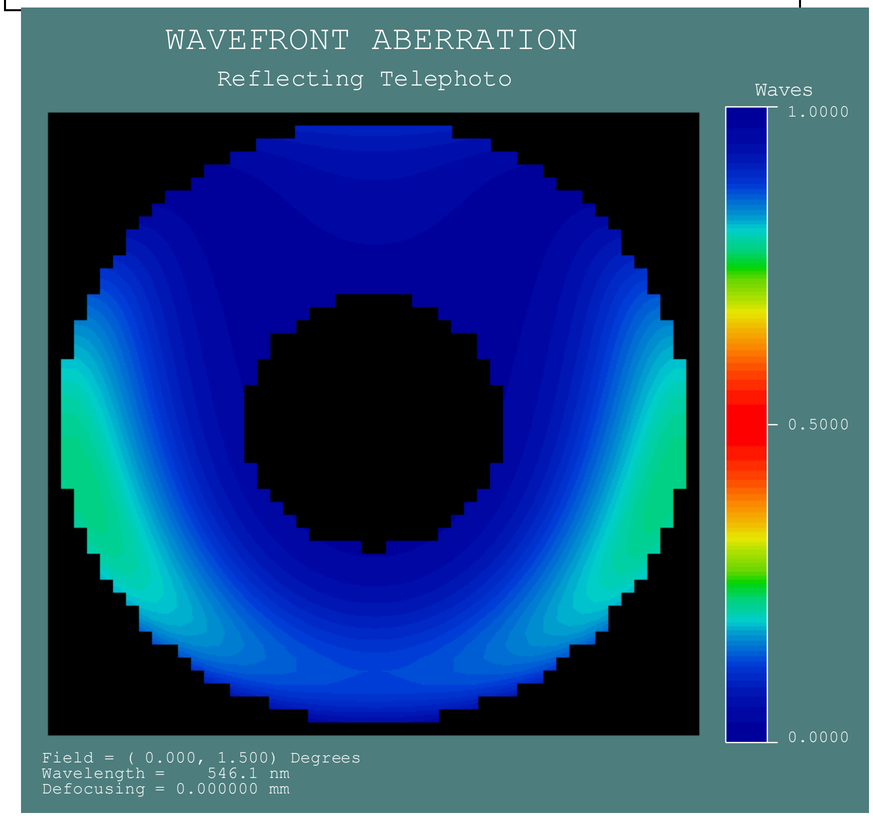
PMA outputs (2)

```
RES CV_LENS:MAKSUTOV
PMA
NRD 50        ! Number of rays across pupil diameter
PLO N         ! Suppress oblique projection plot
CON SUP       ! Draw contours, suppress line numbers
GO
```



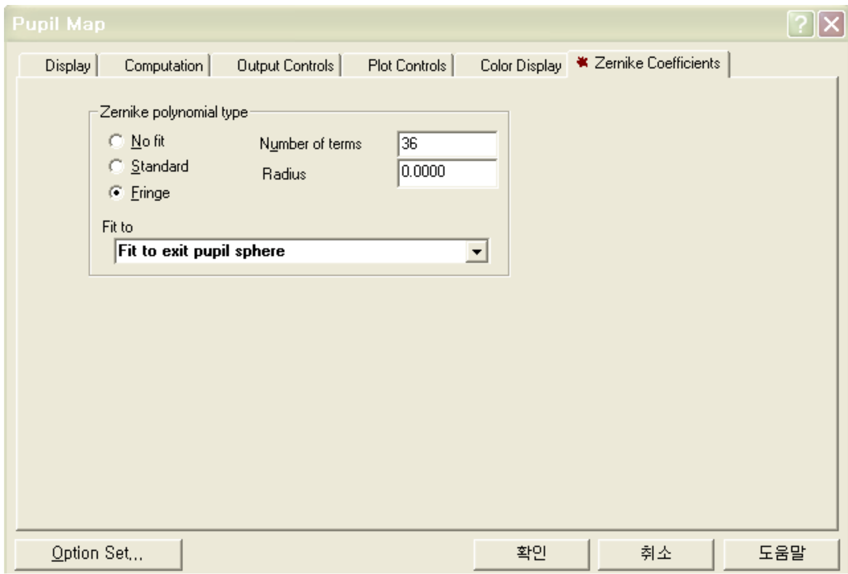
Contour plot with numbers suppressed @f2

```
RES CV_LENS:MAKSUTOV
PMA
NRD 50        ! Number of rays across pupil diameter
PLO N         ! Suppress oblique projection plot
DIS INT Y     ! Draw data as interference fringes
GO
```



Interference fringe @f2

PMA outputs (3)




```
RES CV_LENS:MAKSUTOV
PMA
LIS N          ! Turn off listed output
PLO N          ! Suppress oblique projection plot
ZFR EXS 36     ! Fit with fringe Zernike with 36 terms
GO
```

FRINGE ZERNIKE POLYNOMIAL COEFFICIENTS (normalization radius = 0.570259)

Number	Value (waves at 546.1 nm)	RMS wavefront error
1	0.0684	0.0684
2	0.0000	0.0000
3	-0.0966	0.0483
4	0.0536	0.0310
5	0.1232	0.0503
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0051	0.0018
9	-0.0354	0.0158
10	0.0000	0.0000
11	-0.0046	0.0016
12	0.0204	0.0064
13	0.0000	0.0000
14	0.0000	0.0000
15	0.0381	0.0110
16	-0.0214	0.0081
17	-0.0013	0.0004
18	0.0000	0.0000
19	0.0000	0.0000
20	-0.0027	0.0008
21	0.0037	0.0010
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0019	0.0005
25	-0.0008	0.0003
26	0.0000	0.0000
27	0.0001	0.0000
28	-0.0001	0.0000
29	0.0000	0.0000
30	0.0000	0.0000
31	-0.0001	0.0000
32	0.0000	0.0000
33	0.0000	0.0000
34	0.0000	0.0000
35	0.0000	0.0000
36	0.0000	0.0000

Astigmatism

Coma

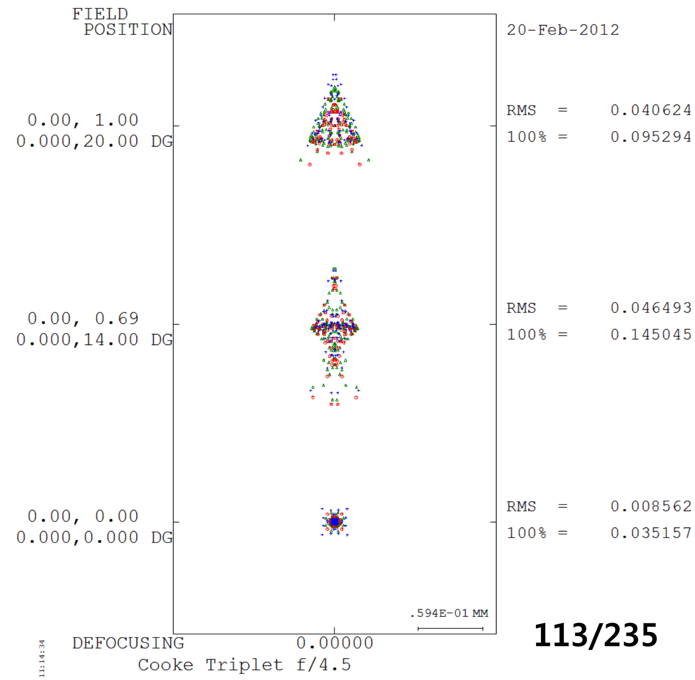
Spherical aberration

RMS of polynomial = 0.0794
(tilt removed) 0.0630
RMS fit error = 0.0000

Spot diagram

- Generates plots of ray intersection with the image surface(S) to represent image characteristics, and calculates and lists RMS spot size and 100% spot size
  - Diffraction is ignored.
- Output is annotated plot plus tabular summary of minimum diameters and image centroid locations for 100% RMS spot diameters
  - Can also overlay Airy disk or detector on plot

```
RES CV_LENS:COOKE1
SPO
GO
```



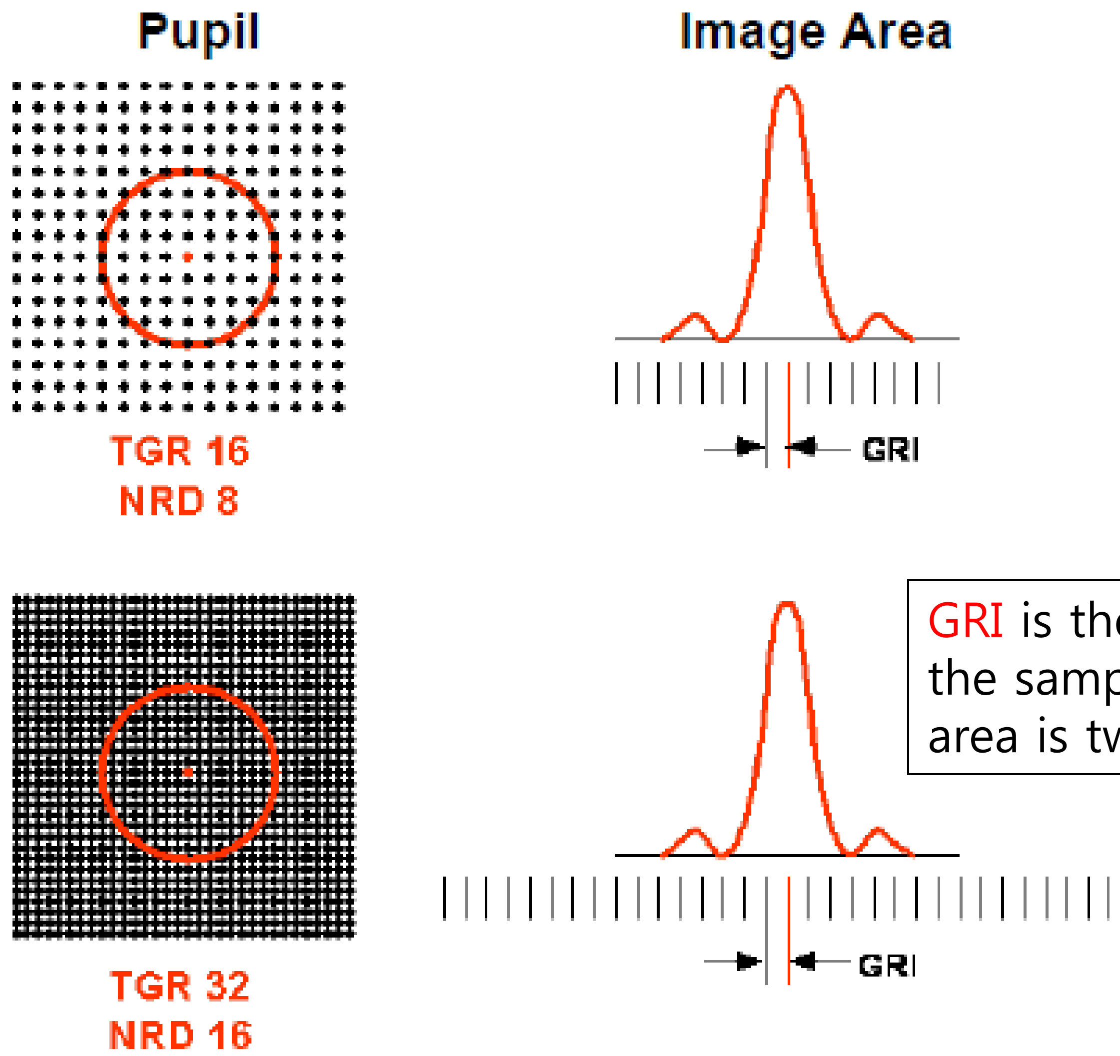
Point spread function

- Computes the characteristics of the image of point objects, including the effects of diffraction

- Uses FFT(Fast Fourier Transform)
  - Due to the nature of the FFT process, if the pupil function is represented by many points, such as the default grid interval provides, the diffraction image will be represented by few points. Thus, asking for a smaller output grid spacing(Focal plane grid increment setting or GRI) to enlarge the image size will provide more detail in the output but will use less data to represent the lens.

- Various types of output
  - Image of a point object
  - Encircled energy
  - Detector convolution
  - Image of two close objects

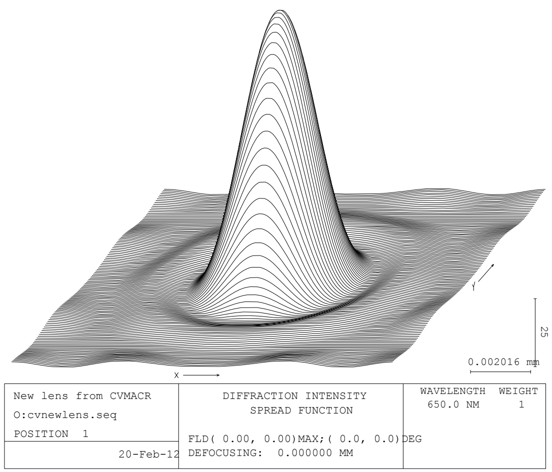
Effects of increasing TGR and NRD by a factor of 2

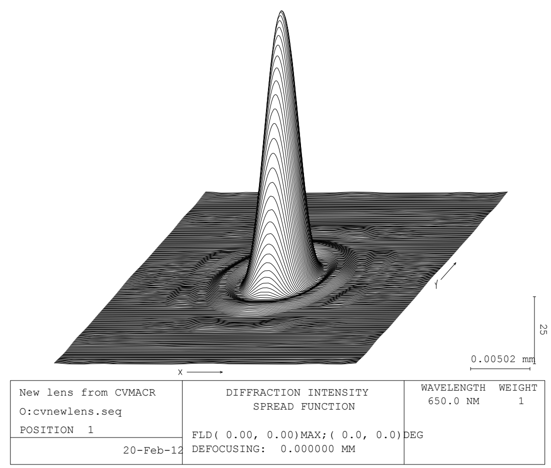


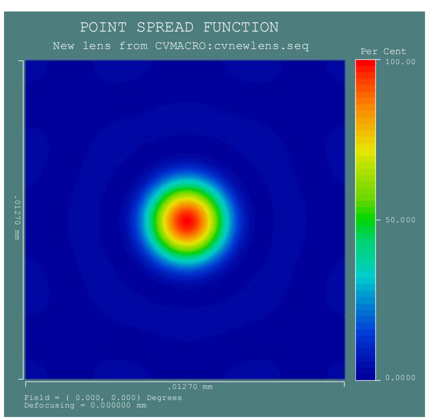
GRI is the same, but the sampled image area is twice as large

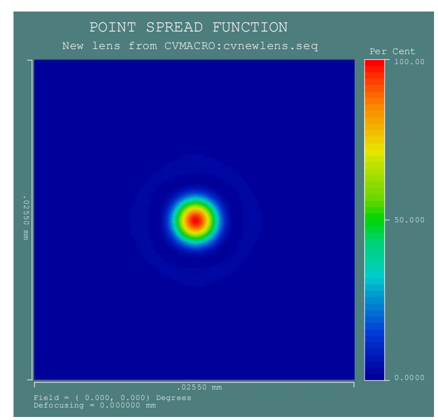
PSF Color display plot @ col_20mm.len

- TGR 128 ; GRI 0.0001
- TGR 256 ; GRI 0.0001









Wavefront aberration

- Computes the RMS wavefront error (with tilt removed) or Strehl ratio for each field at individual best focus and at best composite focus, or optionally, at the current focus (NOM command)

- WAV;NOM;GO

FIELD	FRACT	DEG	RMS (WAVES)	SHIFT (MM.)	STREHL
X	0.00	0.00		0.000000	
Y	0.00	0.00	0.007779	0.000000	0.997614
X	0.00	0.00		0.000000	
Y	0.70	0.60	0.005809	-0.000002	0.998669
X	0.00	0.00		0.000000	
Y	1.00	0.86	0.016366	-0.000003	0.989482
WEIGHTED RMS (WAVES)			0.010986		0.995246

- WAV;(BES);GO

FIELD			BEST INDIVIDUAL FOCUS				BEST COMPOSITE FOCUS			
	FRACT	DEG	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL
X	0.00	0.00	0.000000	0.002166	0.0016	1.000	0.000000	-0.000670	0.0101	0.996
Y	0.00	0.00	0.000000				0.000000			
X	0.00	0.00	0.000000	-0.000630	0.0054	0.999	0.000000	-0.000670	0.0054	0.999
Y	0.70	0.60	-0.000002				-0.000003			
X	0.00	0.00	0.000000	-0.003540	0.0106	0.996	0.000000	-0.000670	0.0146	0.992
Y	1.00	0.86	-0.000046				-0.000003			

- WAV;RFO;GO
  - The defocus term in the lens has been changed by -0.000670

RMS wavefront error

- Peak-to-valley(P-V) WFE is a poor measure of system performance because the effects on resolution are strongly influenced by the aberration content (e.g., spherical, coma, focus, …)

- RMS WFE is a more stable criterion. The generally accepted equivalent to the ¼ wave P-V rule is

  - **RMS WFE < 0.07 waves = "diffraction-limited"**

- This is best studied in detail (P-V to RMS relationships) using Zernike polynomials

- P-V is still commonly seen as a surface figure tolerance where it serves to specify mirror slope errors, especially at the edge of the optical clear aperture

Strehl ratio

- Another commonly referred to criterion, in near diffraction-limited systems, is the Strehl ratio

- Here, the equivalent to the 1/4wave P-V rule is

  - **Strehl ratio > 0.8 = "diffraction-limited"**

- Physically, Strehl ratio is the drop in the central intensity of the Airy disk, relative to a perfect system

For small values of RMS WFE

$$S.R. = 1 - [\,(2\pi/\lambda)^2 (\Delta W_{RMS})^2\,] \quad (W_{RMS} < 0.1 \text{ waves})$$

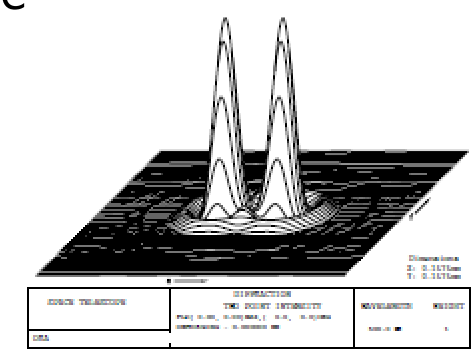
ΔW_{RMS}	0.00	0.035	0.07	0.115	0.15
S.R.	1.0	0.95	0.80	0.50	0.10

Rayleigh ¼ wave rule

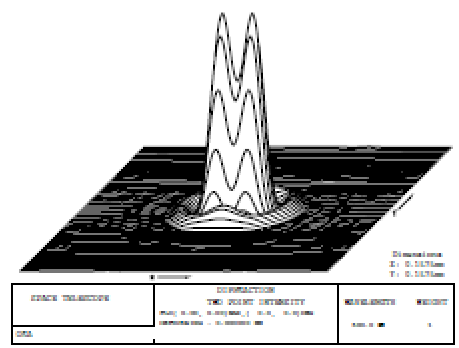
- The ¼ wave rule is not used, but it is the historical basis for the RMS WFE and Strehl ratio criteria that are in frequent use

- The ¼ wave rule was empirically developed by astronomers as the greatest amount of peak-to-valley (P-V) wavefront error that a telescope system could have and still resolve two stars whose spacing satisfied the Rayleigh criterion

- The Rayleigh criterion refers to the spacing of the images; the 1st dark ring of one image overlaps the central maximum of the other image



Well Resolved



Rayleigh

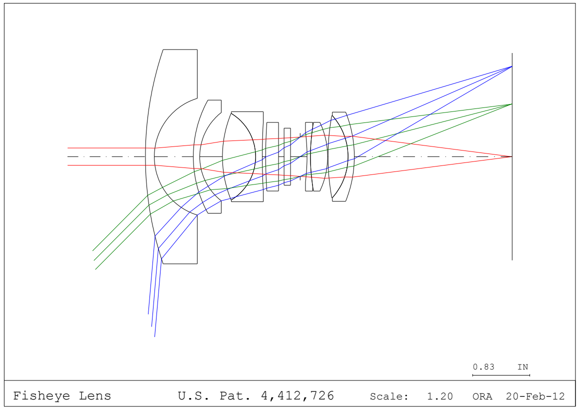
2D image simulation

- Shows the appearance of a "real" graphical object as imaged by the optical system

- Object must be a .BMP file
  - Photograph
  - Drawings/figure
  - Air Force or other resolution target

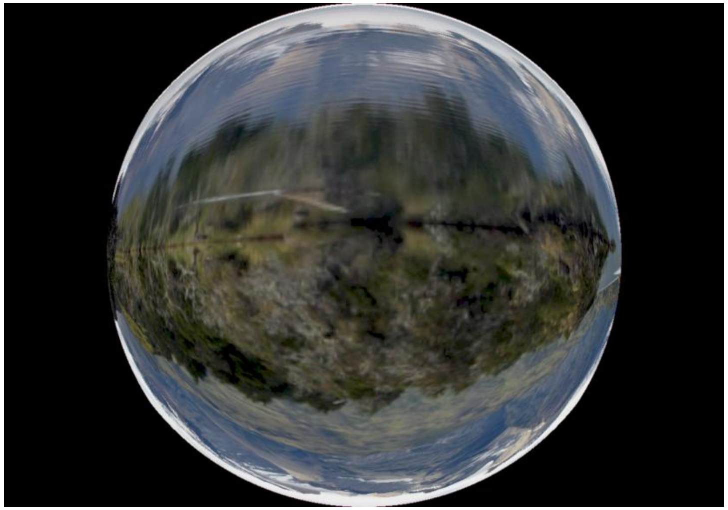
- Effects included
  - Diffraction (convolves with field-varying PSF)
  - Distortion
  - Image orientation (useful for folded systems)
  - Vignetting and other transmission variations
  - Axial & lateral color

IMS sample output



RES CV_LENS:FISHEYE
IMS
OBJ "E:\CODEV103\image\Landscape_Mtn_Lake_1mp.bmp“
CME RGB ! Computes a separate PSF for the red, green, and blue contribution
GO

Object



Image

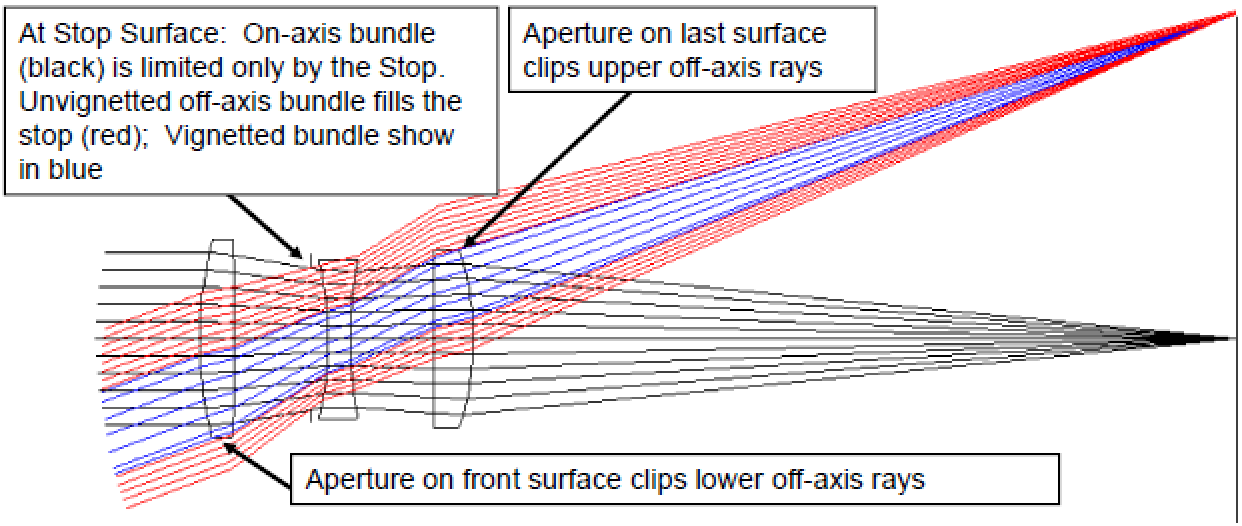
Section 9

Vignetting and aperture

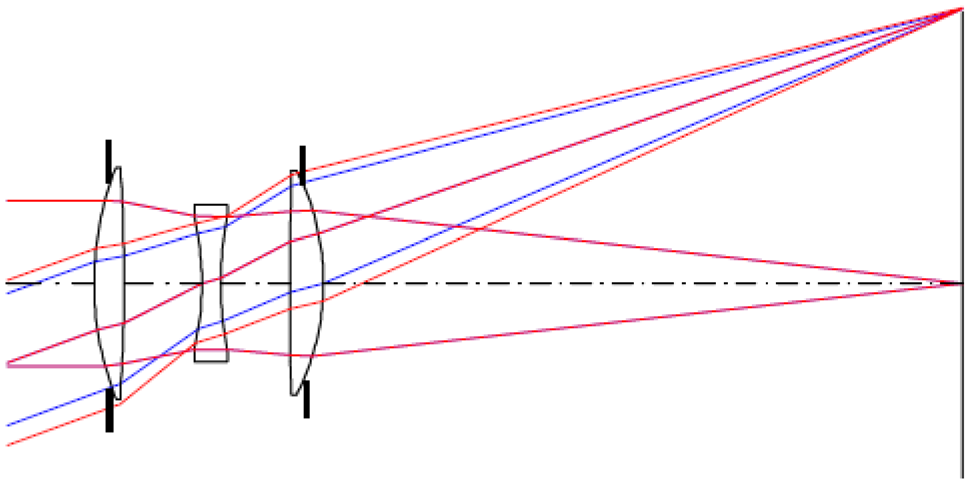
Why are apertures and vignetting important?

- For accurate design and analysis, CODE V must “know” which rays reach the image and which rays do not
  - That is, what is the shape of the cone of light that reaches the image for each field point

- The surface apertures, pupil definition, and CODE V vignetting factors can each be used to determine the ray set that reaches the image for various features of CODE V

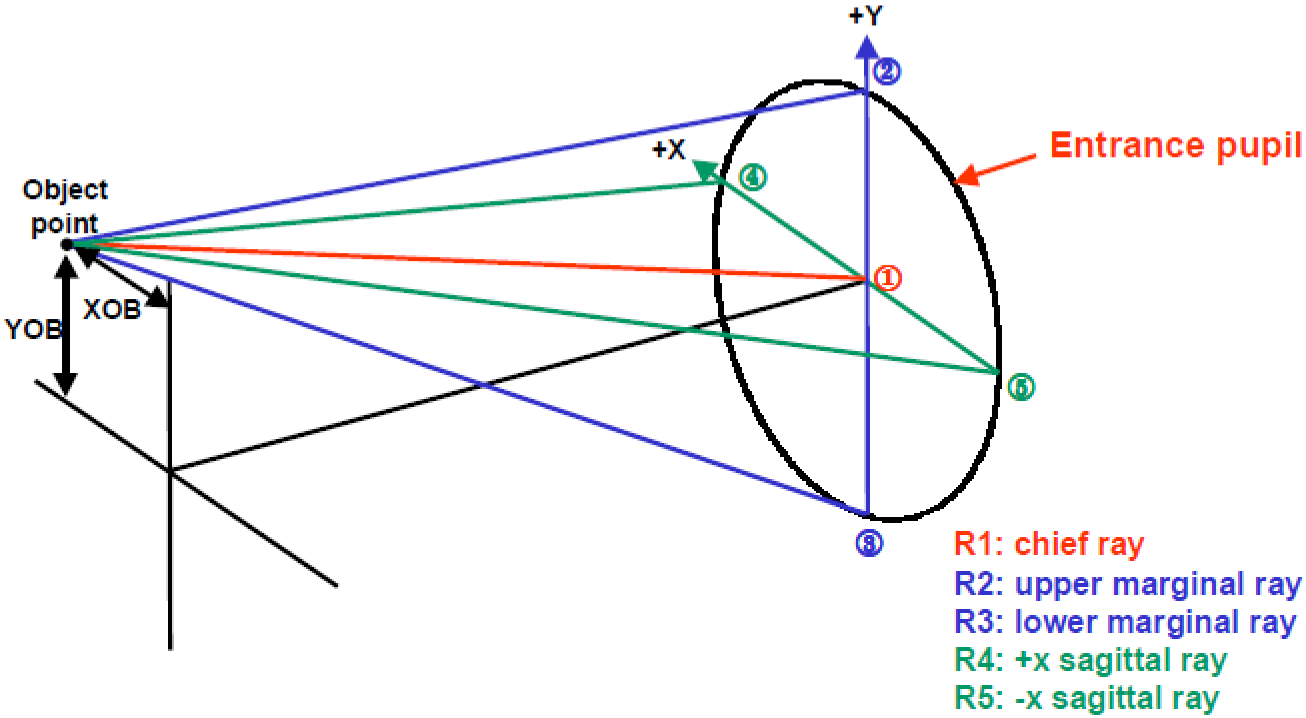


Vignetting



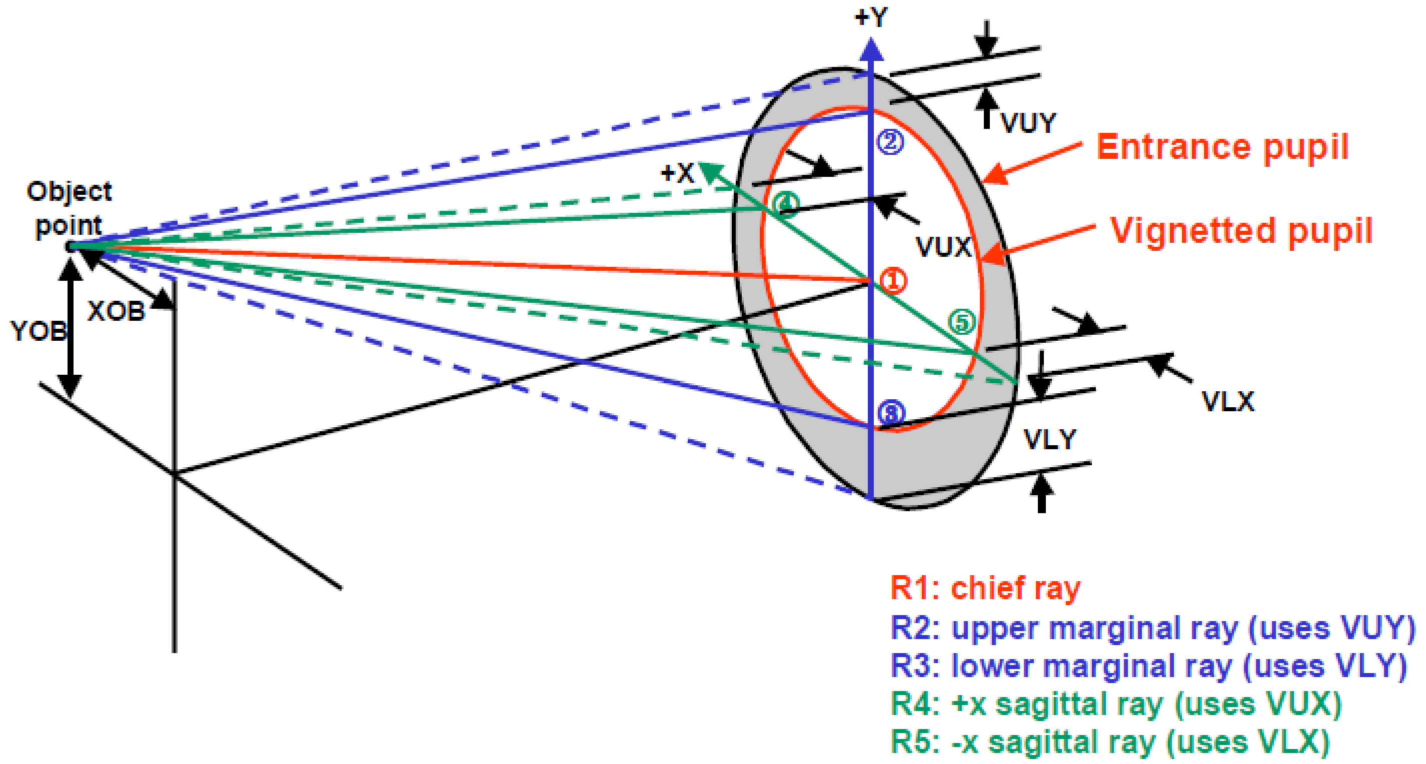
- Caused by user-entered apertures on surfaces
- These apertures clip off-axis rays that would otherwise pass through the aperture stop and hit the image surface
- Useful in reducing large off-axis aberrations
- Sometimes necessary to meet physical restrictions in the lens
- Vignetting reduces off-axis relative illumination in the image

Reference Rays (Zero Vignetting Case)



- 5 Reference rays are traced from each defined field point
- Reference ray data for each surface are saved and used for default aperture calculations (and other purposes)

Reference Rays (Positive Vignetting Case)



- Result in elliptically shaped ray bundle at the entrance pupil

Apertures

- Each surface always has at least one aperture associated with it

- Two classes of apertures
  - Default apertures
    - Generated by the program
    - Apply to all surfaces (except object and image)
    - Based on tracing reference rays
    - Always circular

  - User-defined apertures
    - Entered individually
    - Applies to a specific surface
    - Override the default aperture on that surface
    - Can be circular, rectangular, or elliptical

Default Apertures

- Computed from the reference rays
  - Trace the 5 reference rays from each field (and zoom position) (Remind Entrance pupil)
  - For each surface, retain the value of the maximum radial distance required by any reference ray
  - This value is the semi-diameter of the default aperture

- Only one default aperture per surface
  - Always circular and centered
  - Displayed in Aperture column of main LDM screen

- Note: Default aperture on the stop surface is based on reference rays for field 1 only (controls f/number)

- Default apertures on dummy surfaces do not block rays

User-defined apertures

- Must be specifically entered
- Can be circular, rectangular, or elliptical
- Can be centered, decentered, or rotated with respect to the surface vertex
- Deactivate the default aperture for that surface
- More than one aperture may be entered on a surface
  - If more than one aperture of the same shape is entered, a label is required to differentiate them
- Four types of user-defined apertures
  - Clear aperture, obscuration, edge, hole
- Indicated with a "u" in the Aperture column of the LDM screen
  - Any aperture other than a circular, centered, unlabeled clear aperture is shown as "Special" in the Aperture column
- User-defined apertures on dummy surfaces do block rays

Types of User-defined apertures

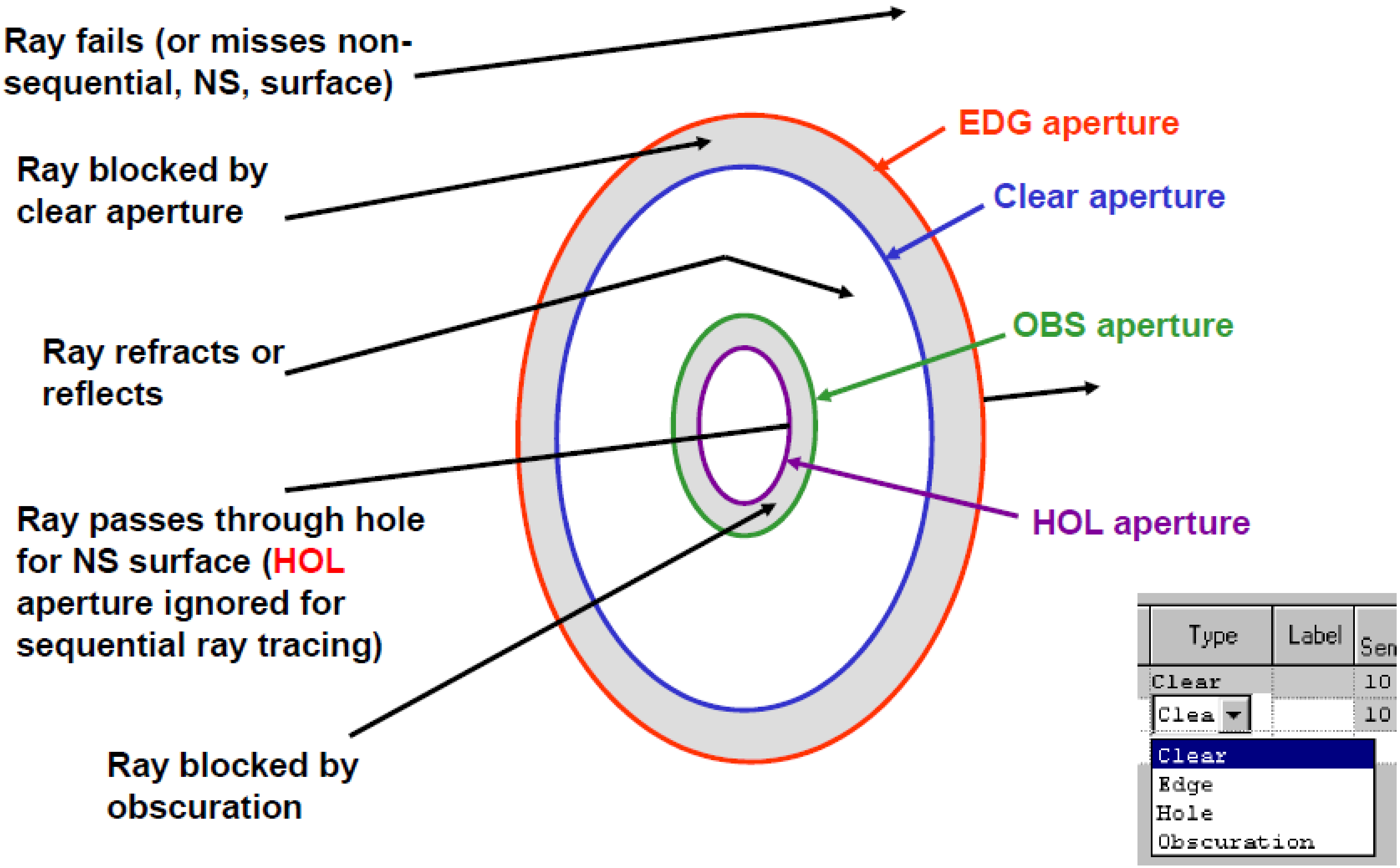
- Clear aperture
  - Most commonly used type
  - Blocks rays outside the aperture

- Obscuration (specified by OBS qualifier)
  - Blocks rays inside the aperture
  - Drawn as a hole

- Edge aperture (specified by EDG qualifier)
  - Does NOT block rays
  - Defines physical size of lens
  - Usually only used in NSS systems

- Hole (specified by HOL qualifier)
  - Does NOT block rays
  - Acts like an "inner edge"
  - Normally only used in NSS systems

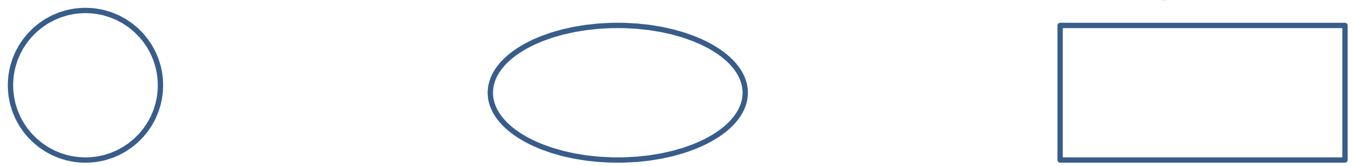
CODE V apertures illustrated



User-entered apertures

- Currently, CODE V supports three shapes for user-entered apertures:

Circular (CIR) Elliptical (ELX, ELY) Rectangular (REX, REY)



- Commands always use the semi-aperture

CIR Sk [CLR|EDG|OBS|HOL] [L'label'(3)] radius
REX Sk [CLR|EDG|OBS|HOL] [L'label'(3)] x_half_rect
REY Sk [CLR|EDG|OBS|HOL] [L'label'(3)] y_half_rect
ELX Sk [CLR|EDG|OBS|HOL] [L'label'(3)] x half ell
ELY Sk [CLR|EDG|OBS|HOL] [L'label'(3)] y_half_ell
DEL APE Sk|Si..j [CLR|EDG|OBS|HOL] [L'label'(3)]

How apertures are used

- Limit the bundles of light in all image evaluation options
  - MTF, PSF, WAV, SPO, etc

- Not used in diagnostic options
  - FIE, RIM, ANA, etc.

- Not used in optimization (except MTF optimization)

- CA flag determines which classes of apertures are used
  - CA YES use both default and user-defined apertures (default)
  - CA NO use default apertures only
  - CA APE use user-defined apertures only
  - Note that a default aperture on the stop surface acts like a user-defined aperture
    - If the user tells CODE V to only use user-defined apertures and then does not enter any, CODE V assumes an aperture on the stop surface only

Making apertures & vignetting consistent

- CODE V can "set" (calculate) the vignetting factors to make them consistent with user-entered aperture
  - SET VIG

- You can also "set" the pupil specification (entrance pupil diameter, numerical aperture in object or image space, or f/number) to be consistent with the apertures
  - SET EPD, SET NA, SET NAO or SET FNO

- CODE V can also "set" or create apertures for you that are consistent with the current vignetting
  - Must delete existing apertures to recalculate
  - SET APE, SET CAP, SET AAP, SET SAP

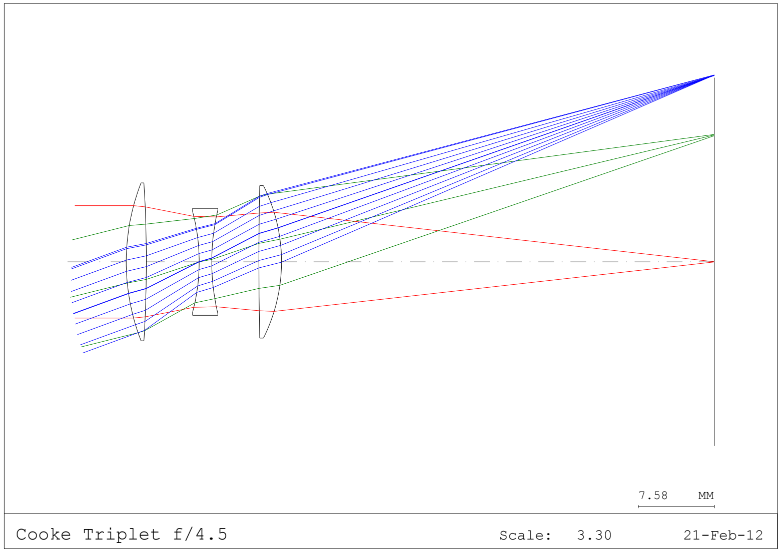
Workshop

- Restore the Cooke triplet lens
  - RES CV_LENS:COOKE1

- View the lens
  - TOW;VIE;FAN F3;GO

- List aperture list
  - APE SA

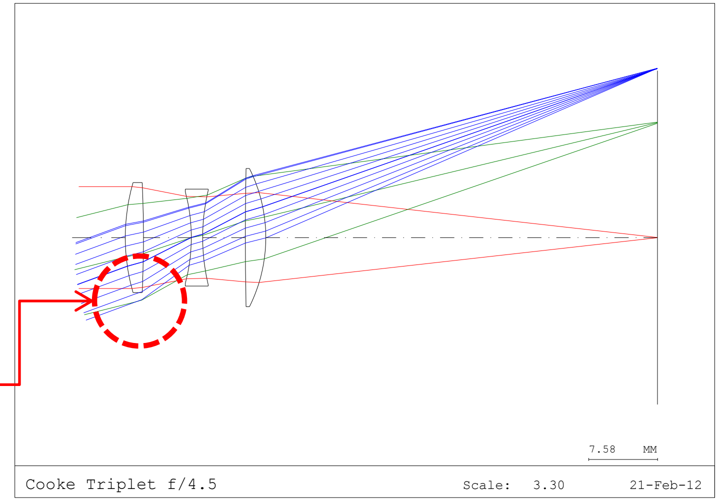
APERTURE DATA/EDGE DEFINITIONS
CA
CIR S1 7.000000
CIR S5 6.500000



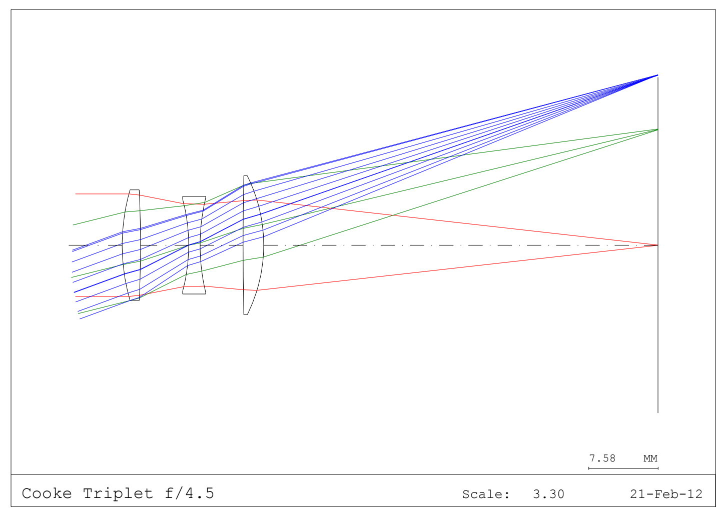
Workshop

- Add circular clear & edge apertures to S1 with a semi-diameter of 6.0mm, re-execute the plot
  - CIR S1 6;CIR S1 EDG 6

Inconsistent



- Set the vignetting and re-execute the plot
  - SET VIG



Section 10

Control codes and solves

Defining Variables and Control Codes

- In the optimization options, including Automatic Design (AUT), Test Plate Fitting (TES), and Zoom Cam Design (CAM), lens parameters, such as radii, thicknesses, and glasses, can be variables for improving image quality and controlling constraints

- Control codes are used to specify whether these parameters are variable, frozen, or coupled to another variable.

- VAR Sk | Si..j
  - Generate all possible variable(s) on designated surface(s)

- FRZ Sk | Si..j
  - Freeze all variable(s) on designated surface(s)

Coupling codes and individual variables

- Coupling codes
  - Variable(0) : free to vary independently
  - Frozen(100) : Not allowed to vary
  - 1 to 99 : Coupling group number. The variable is coupled to all other variables of the same type(and same zoom status) which have the same control code(+ or -)

- CCY Sk | Si..j 0 | 100 | num_of_coupling_grp [....z]
  - Vary/freeze/couple Y Radius/Y Curvature (RDY/CUY)

- THC Sk | Si..j 0 | 100 | num_of_coupling_grp [....z]
  - Vary/freeze/couple thickness(THI)

- GLC Sk | Si..j [A | B | C | D | E | IND | DLN] 0 | 100 | num_of_coupling_grp [....z]
  - Vary/freeze/couple glass(GLA)
  - Qualifiers
    - Omitted – vary both index and dispersion of a fictitious glass
    - A,B,C,D,E – Only moves to boundary
    - IND – Vary index only
    - DLN – Vary dispersion(N_F-N_C) only

Solves

- Solves generate surface data based on a specified condition (usually based on paraxial rays)

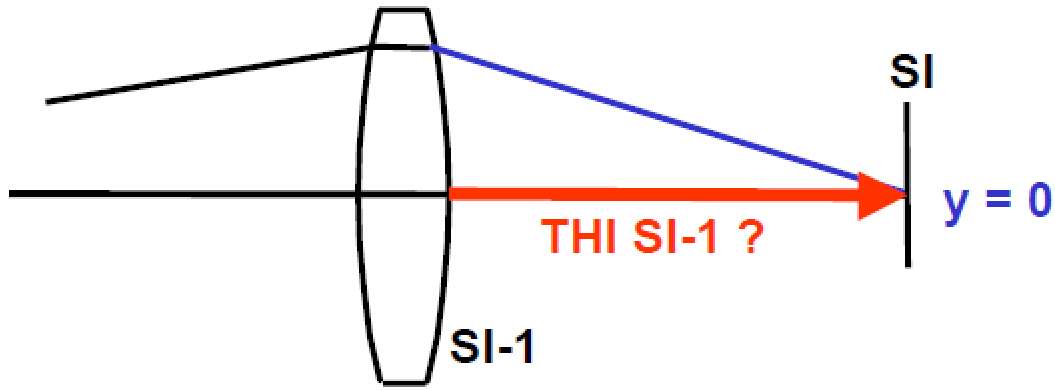
- Two types of solves (many types of each)
  - Curvature solves
  - Thickness solves

- Solves are used to help set up systems and to reduce the number of variables and constraints used in optimization

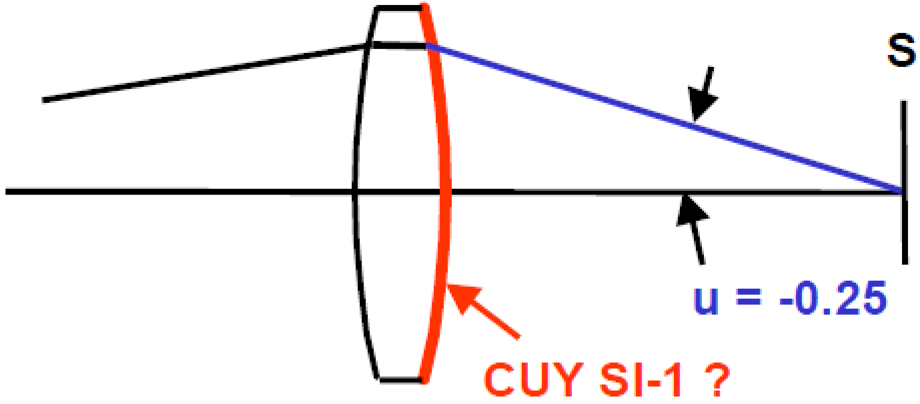
- Note that to use most solves, you must use object-side pupil specification (EPD or NAO) and object-side field specification (XAN/YAN or XOB/YOB)

Example of solves

- Paraxial image solve – solves for image distance (command : PIM)

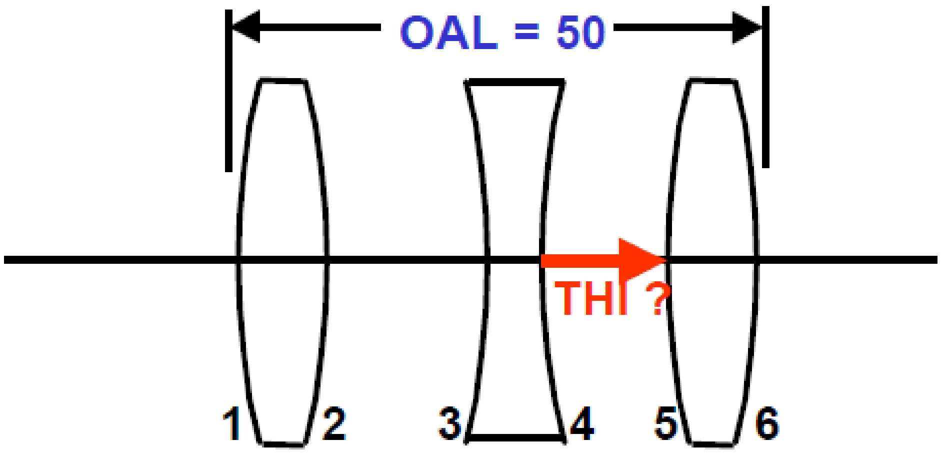


- Curvature solve for marginal slope angle (command : CUY UMY SI-1 -0.25)

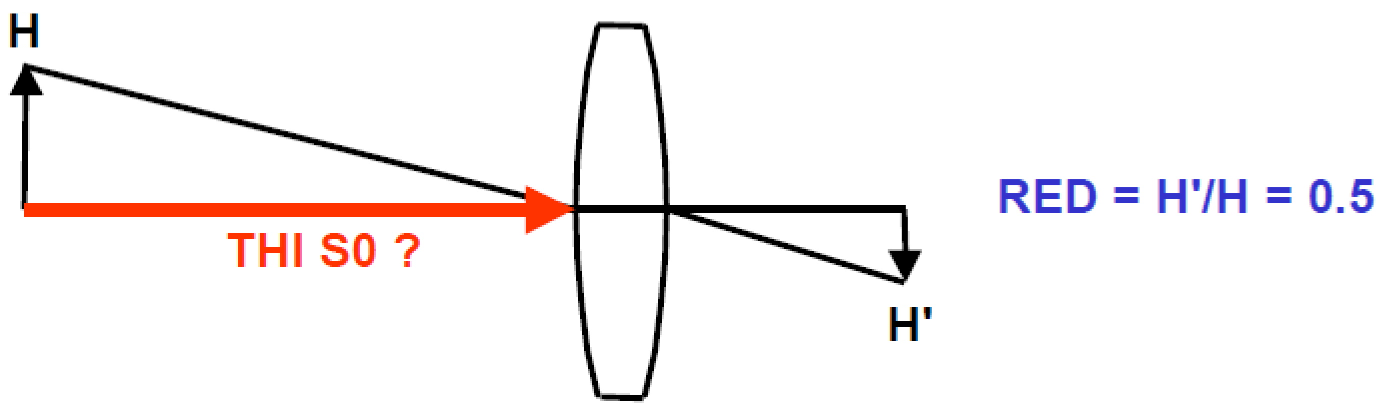


Example of solves

- Overall length solve (command : THI S4 OAL S1..6 50.0)



- Reduction ratio solve – solves for object distance (command : RED 0.5)



Section 11

Afocal systems

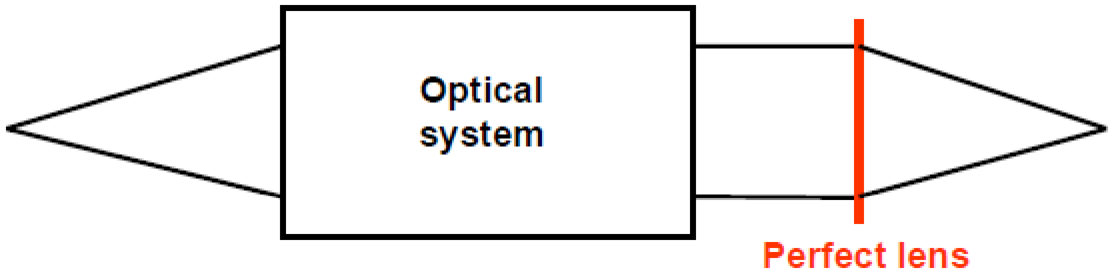
Afocal systems

- An afocal system forms no image (the exiting light is collimated)
  – Normal optical image evaluations, such as spot diagrams, etc., are not usually applicable

- In CODE V, there are two ways to analyze such systems
  – Use a “perfect lens” to focus the light without introducing any additional aberrations
  – Analyze the “image” in terms of its angular deviations from perfectly collimated light (true afocal mode)

- Each of these two ways has advantages for a given system or type of analysis
  – The choice of which to use is usually the preference of the user

The afocal perfect lens



- Perfect lens properties:
  - Thin lens, nodal points in contact
  - Perfect imaging at one conjugate pair
  - No spherical aberrations of nodal points

- Two types of perfect lens
  - **AFI** (afocal, infinite conjugates)
    - Perfect at infinite conjugates (most common case)
  - **AFO** (afocal, any conjugates)
    - Perfect at used conjugates
    - Primarily used to convert f/numbers

Use of the afocal perfect lens

- The perfect lens is always placed on a dummy surface just before the image surface (surface SI-1)
  - It cannot be the back side of an element (must have air on both sides)
  - The thickness of this surface is normally set to be equal to the perfect lens focal length (for collimated light input)
- In general, do NOT use a PIM solve or a defocusing variable with AFI
  - Otherwise, it allows the incoming light to be non-collimated and still be in focus at the image
  - The nature of the perfect lens is to force perfect collimation during optimization
- The use of AFO is to convert f/numbers (e.g., change a slow system to a faster system)
  - Can simulate a perfect relay lens or imaging lens
  - Often can be done better with a Lens Module

Section 12

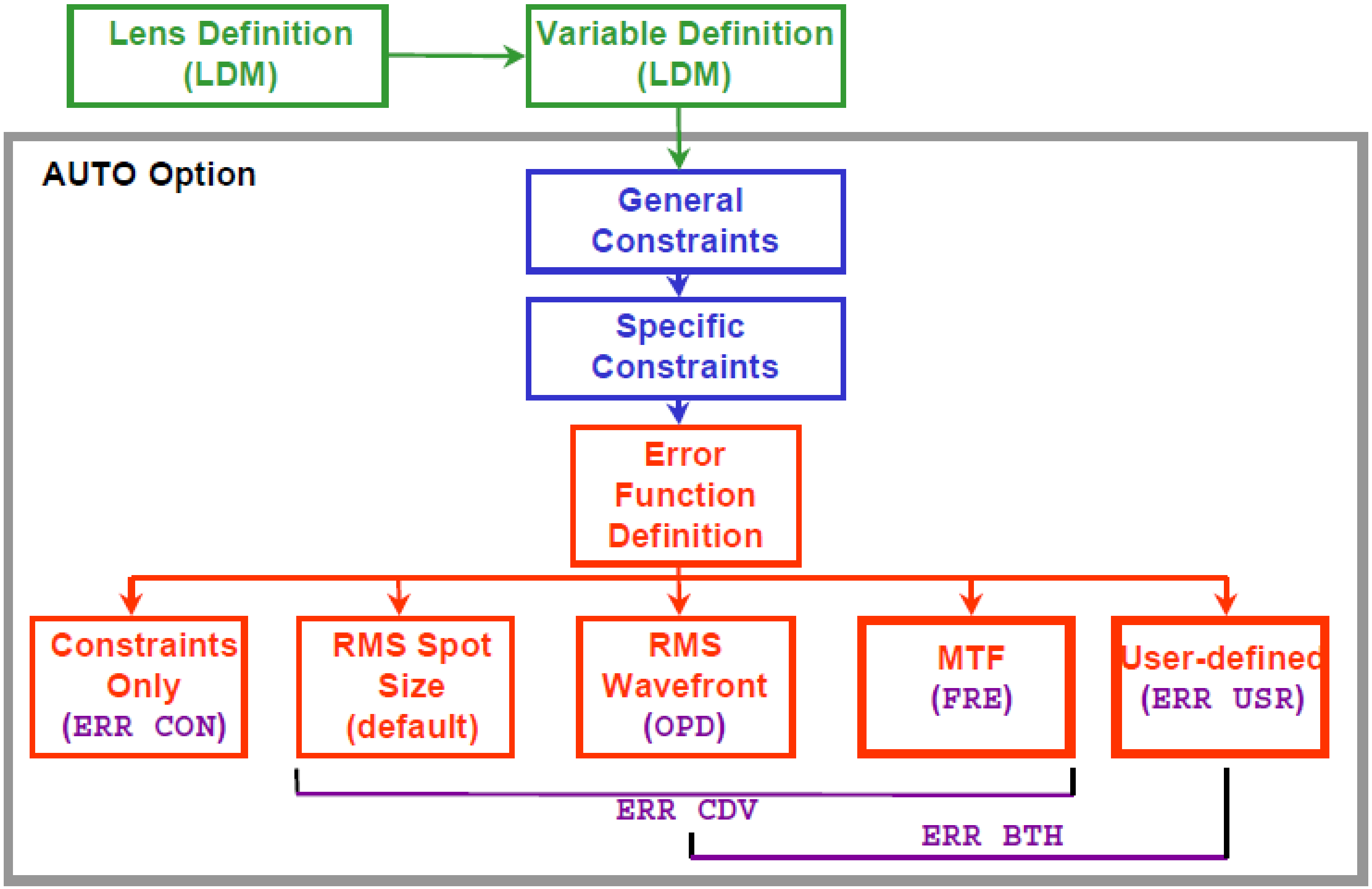
Automatic design

Goal of automatic design(optimization)

- Best performance that can be achieved, subject to problem constraints

- Requires
  - A defined error function (sometimes called a “merit function”)
  - A process to improve the error function
  - A method of controlling boundary conditions (constraints)

Schematic map of AUTO



What is an error function?

- A single positive number that represents the quality of the optical system

- Structured such that smaller values are better than larger values
  - 0 is the best error function

- Usually related to aberrations or image error

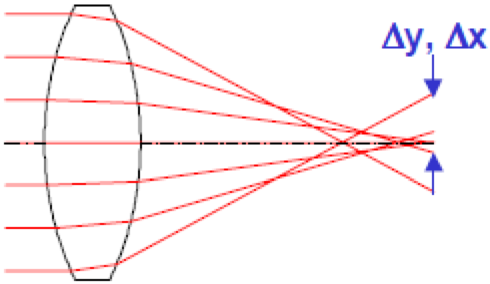
- Can include contributions representing non-image error constrains
  - Usually not need in CODE V

CODE V error function

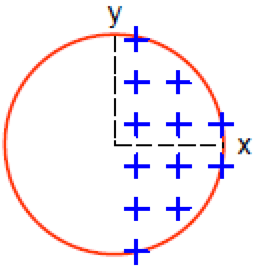
- Five types of error functions in CODE V
  - Weighted transverse ray aberrations (default)
  - Wavefront variance (OPD based)
  - MTF
  - Fiber coupling efficiency
  - User-defined

- Constrains only image errors in the default case
  - Constrains are handled separately
  - Constrains can be included if desired (with WTC request)
    - Seldom necessary in practice

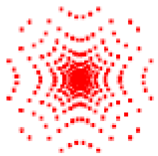
Default CODE V error function



Transverse aberrations Δx and Δy measured from chief ray



Ray distribution in pupil
12 ray, all skew pattern



Tight core with some flare

- Default error function is basically a weighted RMS spot size
- Transverse ray aberration(ΔX and ΔY from chief ray)
- All skew rays (no rays on meridional or sagittal planes)
  - Traced for each wavelength, field, and zoom position
- Weighting is used
  - Wavelength weighting (default is same as LDM)
  - Field weighting (default is same as LDM, users may wish to override this)
  - Aperture weighting (default tries for tight core with some allowed flare)

Reducing the error function

- CODE V uses a damped least squares (DLS) method of optimization
  - Very effective at finding the local minimum

- Two types of optimization
  - **Local optimization**
    - Finds the nearest local minimum in error function space
    - Most commonly used method
  - **Global optimization**
    - Done with Global Synthesis®
    - Finds multiple solutions (multiple local minima), each optimized and meeting all constraints
    - It has a special search algorithm to find potential solutions, then uses local optimization to find each solution
    - Takes significantly longer than local optimization
    - Not covered in this seminar

How CODE V handles constraints

- CODE V uses a method called Lagrange Multipliers
  - Separates the constraint control from the error function
  - Provides very precise control of constraints

- Constraints are only imposed when necessary
  - Allows CODE V to operate in a least constrained mode

- Constraints can be equality constraints or bounded constraints (single-sided bounds or double-sided bounds)

EFL = 100

OAL S1..I < 100

IMD > 70 < 80

Two classes of constraints

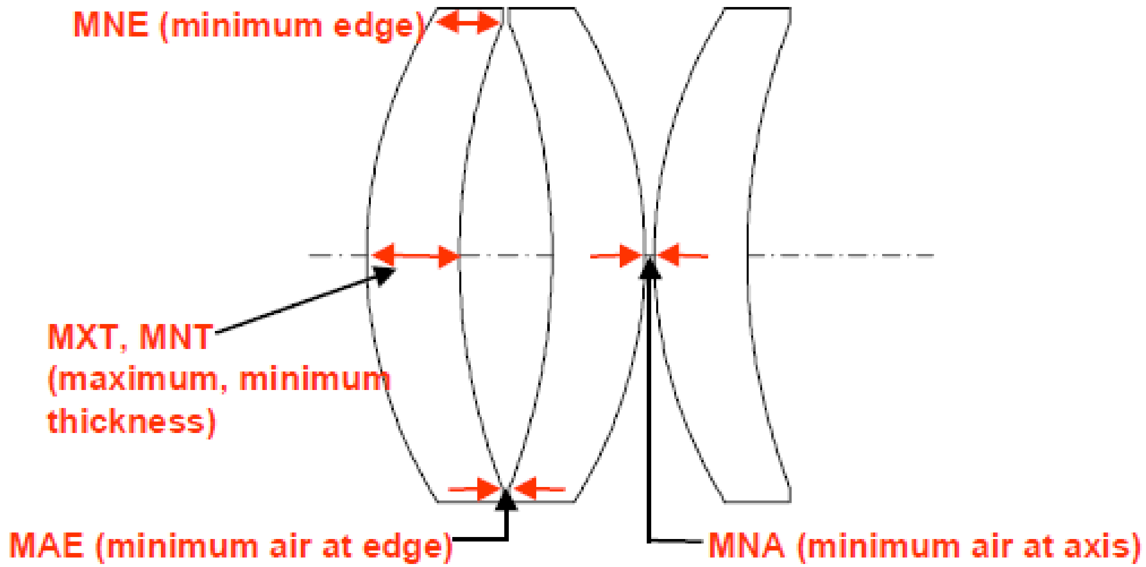
- General constraints
  - Applied by default
  - Apply to all surfaces and zoom positions
  - Have default values, which can be overridden
  - Always controlled with Lagrange multipliers
  - Are always bounds

- Specific constraints
  - Applied by request only
  - Apply to a specific surface and specific zoom position
  - Can be controlled by Lagrange multipliers (default) or included in the error function
  - Can be equality targets or bounds

General constraints

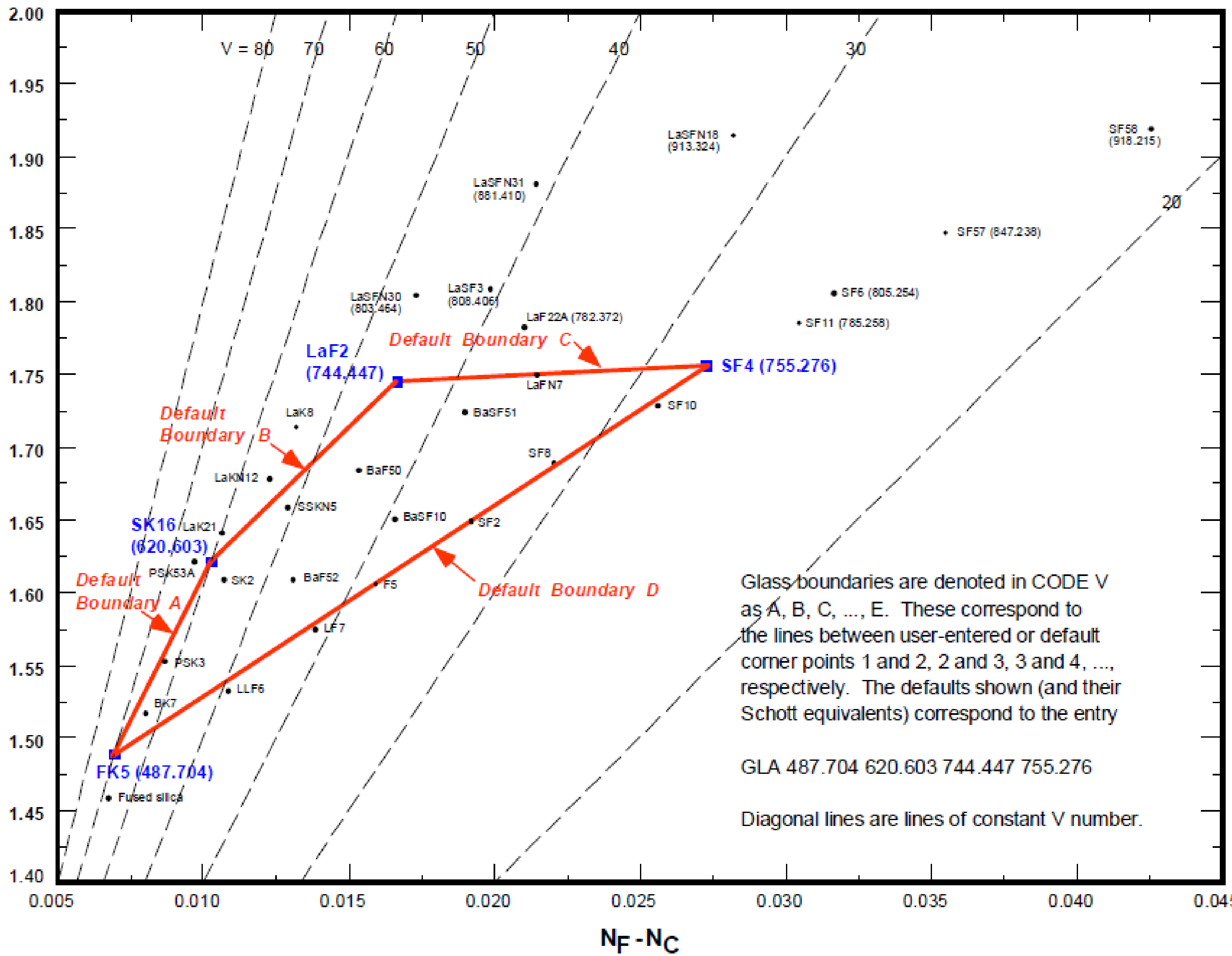
- MXT - Maximum thickness of an element
- MNT - Minimum thickness of an element
- MNE - Minimum edge thickness of an element
- MNA - Minimum axial air spacing between elements
- MAE - Minimum air spacing at edge of elements
- GLA - Constraints on n_d and dn for variable glasses
- MXA - Maximum angle of incidence of any reference rays
  - Not applied by default
  - Useful for Global Synthesis runs

General constraints



- Apply to a surface ONLY if the corresponding thickness is a variable
- Always active in all zoom positions
- If MNE and MXT are in conflict, MNE is satisfied (MXT violated as needed)

Glass boundaries

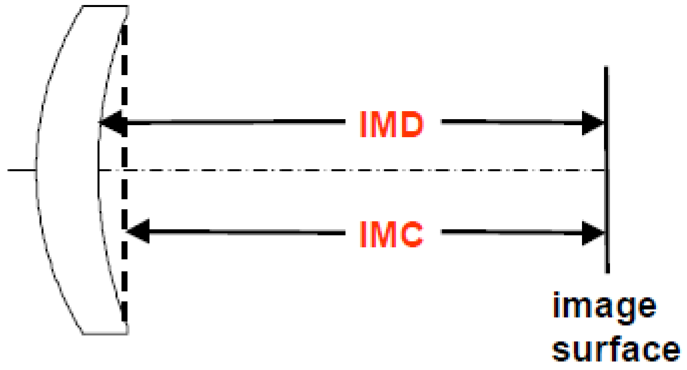


Common specific constraints

- EFL – Effective focal length of entire lens
  EFL = 50

- EFX, EFY – Effective focal length of a group of surfaces(X or Y meridian)
  EFY S7.. 10 = 100

- IMD, IMC – Image distance, image clearance (includes defocus)
  IMC > 25



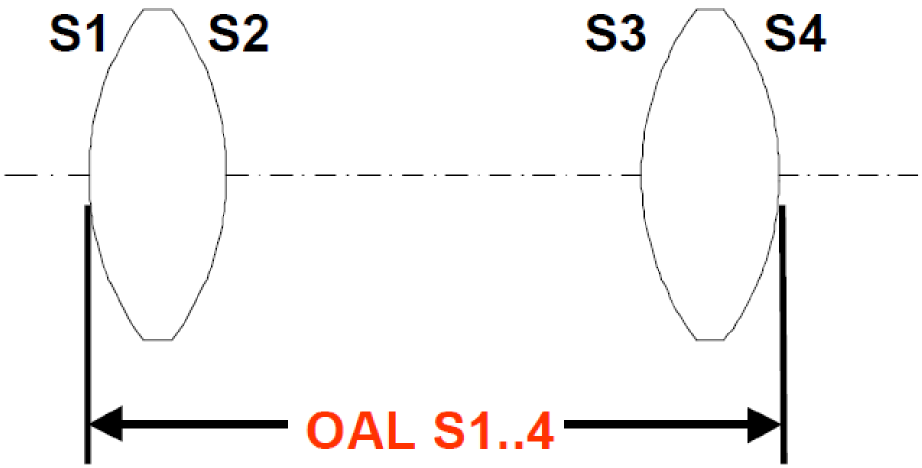
Common specific constraints

- Paraxial constraints at any surface
  HMX, UMX, IMX, HMY, UMY, IMY
  HCX, UCX, ICX, HCY, UCY, ICY
  UMY S7 = 0 ! force paraxial collimation after surface 7

- Third-order aberrations
  SA, TCO, TAS, SAG, PTB, DST, AX, LAT, PTZ
  SA = 0 ! zero third-order spherical aberration
- Distortion at a specified field
  DIX, DIY
  DIY F3 > -0.01 < 0.01 ! distortion held within ±1%

Common specific constraints - mechanical

- CT Sk - Center thickness after surface k
  CT S5 < 5.0
- ET Sk - Edge thickness between surface k and surface k+1
  ET S3 > 2.0
- OAL Si..j - Overall length between surfaces i and j
  OAL S1..4 < 50



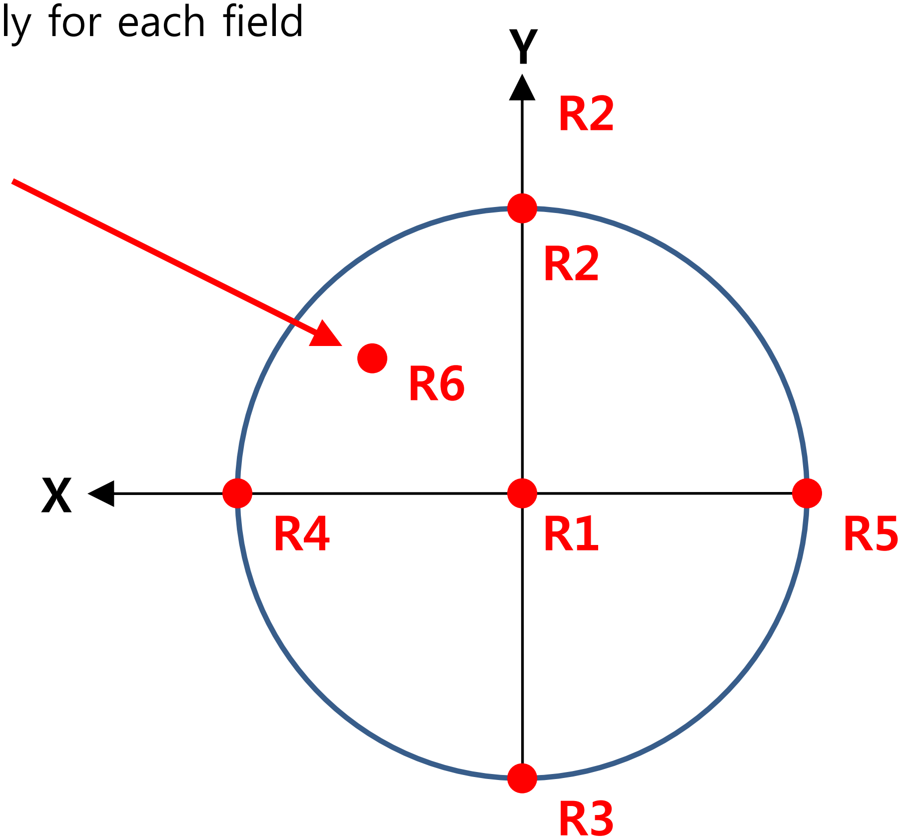
- Important note: Specifying a CT or ET for a surface disables ALL general constraints for that surface for ALL zoom positions

Constraints on reference rays

- Constraints may be made on any reference ray at any surface
  - Traced in any wavelength (default is reference wavelength)

- 5 reference rays are pre-defined (R1 to R5)
  - Up to four more may be defined (R6 to R9)
    - Defined separately for each field
  - Syntax is

    RAY R6 F3 0.5 0.5



Constraints on reference rays

- Available quantities for any reference ray at any surface

X, Y, Z	x, y, z surface coordinates
L, M, N	l, m, n direction cosines
OP Si..j	optical path length between surfaces i and j
SRL, SRM, SRN	direction cosines of surface normal at intersection

- All are defined in local surface coordinates unless Gj (global) qualifier used

- Examples (see figure)

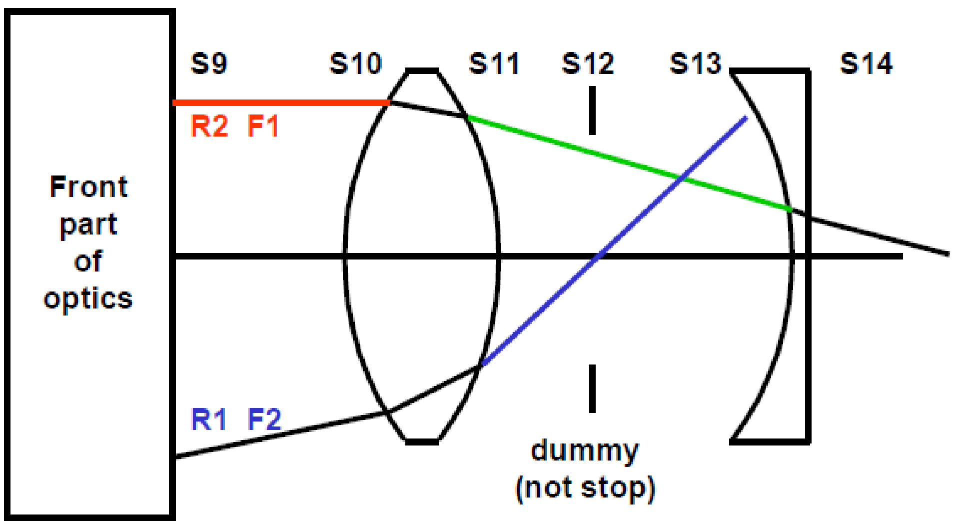
  M R2 F1 S9 = 0

  (UMY S9 = 0)

  Y R1 F2 S12 = 0

  (HCY S12 = 0)

  Y R2 F1 S13 < 5



User-defined constraints

- User-defined constraints (UDCs) allow you to define almost any constraint you need
  - You can refer to lens constructional data, ray trace data, or first-order data in defining the constraint, as well as any Macro-PLUS functions
  - UDCs can use other UDCs in their definition
  - They all have a name starting with @

- First they must be defined

  @UDCNAME == (expression)

- Then they are used as any other constraint

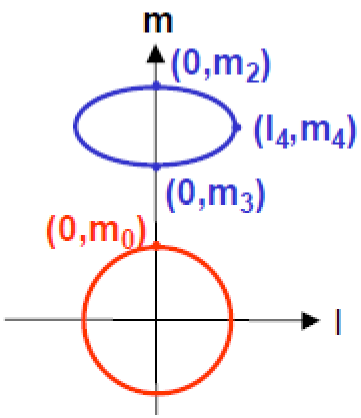
  @ABC = 100

  @XYZ < 20

UDC example – relative illumination

- Relative illumination is the ratio of the off-axis pupil area to the on-axis area, as measured in direction cosine space

- In many systems, the pupil area can be approximated by an ellipse



Relative illumination

$$\frac{(m_2 - m_3) * l_4}{2 * m_0^2}$$

m_0 = (M F1 R2 SI)
m_2 = (M F2 R2 SI)
m_3 = (M F2 R3 SI)
l_4 = (L F2 R4 SI)

@RI == ((M F2 R2 SI)-(M F2 R3 SI))*(L F2 R4 SI)/(2*(M F1 R2 SI)**2)
@RI > 0.60

User Modifications to the Default Error Function

- Common changes
  - Changing number of rays (DEL)
  - Changing weight on aperture (WTA)
  - Changing weight on wavelength (WTW)
  - Changing weight on fields (WTF)
  - Use of wavefront variance (WFR)
  - Use of D-d method for faster color correction (DMD)

- Less common change
  - Adding constraints directly into the error function (WTC)
    - Weight selection is important
  - Optimizing on constraints only (ERR CON)
  - User-defined error function (ERR USR)
    - You do all the work to define rays, aberrations, weights, targets, etc.

Weight on Field and Aperture in AUTO

- Weight on field default (WTF)
  - AUTO uses LDM WTF values, which are unity by default. It is often desirable to weight the center of the field more heavily for optimization.
  - For example: WTF 1.0 .875 .50 .3 .1 for 5 fields
  - Can split into X and Y components (WTX and WTY)

- Weight on aperture (WTA)

  $W(x,y) = 1/(x2+y2)^{WTA}$

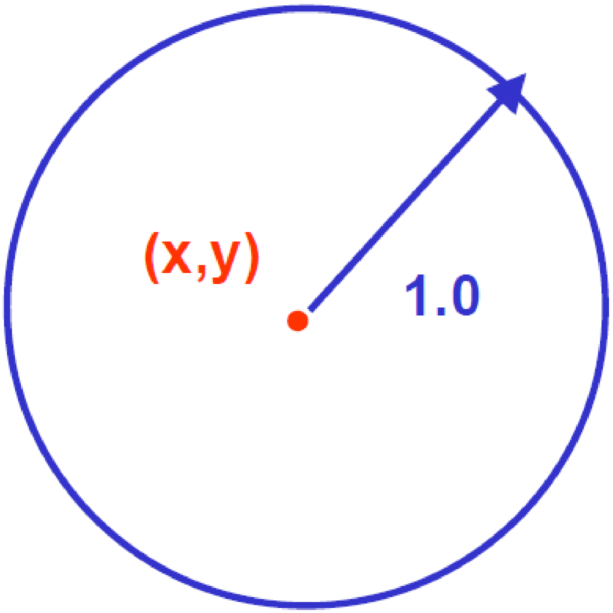
  - WTA default = 0.5

    W = 1/r

    - Note all rays are skew rays so W never goes infinite

  - For OPD mode, WTA = 0

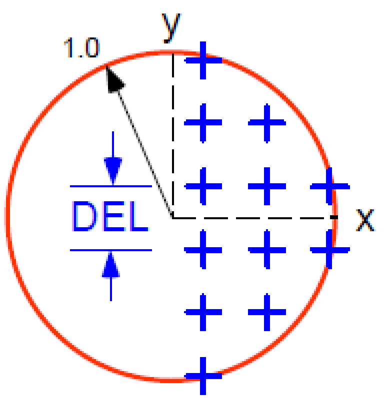
    W = 1.0 for all rays



Control of Rays Used in Optimization

- DEL value - controls ray delta spacing in pupil

DEL	Rays in half pupil	
1.414213 - .632456	2	
.632455 - .471405	6	
.471404 - .392233	8	
.392234 - .342998	12	(0.385 default)
.342997 - .282843	16	
.282842 - .262613	22	
.262612 - .232496	26	
.232495 - .220864	30	
.220863 - .210819	34	(0.22 default for ASP)
...		
- .020000	3930	



DEL 0.385 (default)

- OBS value - obscures rays inside a specified relative radius

- MER, SAG Y|N - rays are collapsed to meridional or sagittal plane (used mainly for cylindrical systems)

- SAP Y|N - square aperture pattern (fills in corners of ray pattern)

Saving Time in AUTO

- Especially useful for Global Synthesis runs, or local optimization of complicated systems
- Use the minimum number of wavelengths
  - Monochromatic, if possible
  - 2 or 3 is usually sufficient for polychromatic system
    - Only apochromats require more wavelengths
  - DMD gives faster color correction

- Use the minimum number of fields and zoom positions

- Retain YZ symmetry whenever possible
  - Use only Y fields and Y tilts/decenters

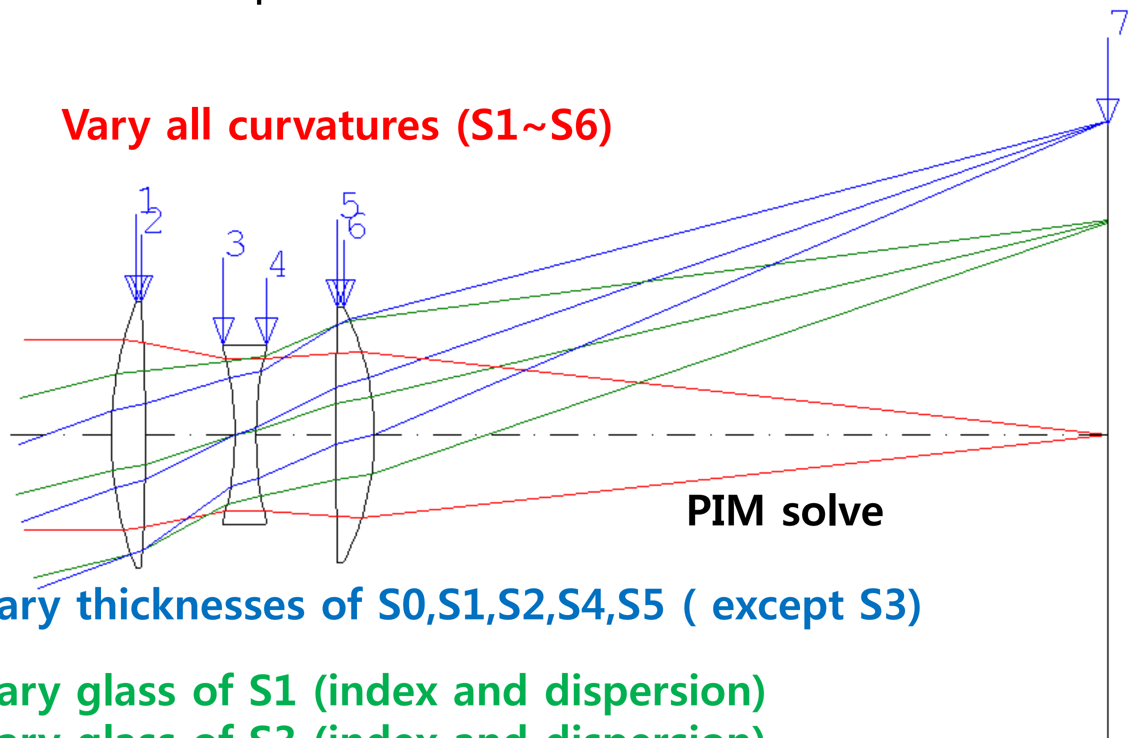
- For local optimization, use a reduced variable set, particularly in the early runs
  - Thicknesses can often be frozen without much impact
  - Variable glasses can often be frozen to boundaries

Exit controls

- INT Yes | No - Interactive mode (default No)
- MXC – Maximum number of permitted cycles (default 25)
- MNC – Minimum number of required cycles (default 2)
- TAR – Upper and lower limits for the error function
- IMP – Improvement fraction control

Workshop

- Start with f/4.5 Cooke triplet
  - RES CV_LENS:COOKE1
- Change to f/2.8 and optimize



- 16 variables

Defining variables

- SUR SA F

	RDY	THI	RMD	GLA	CCY	THC	GLC
> OBJ:	INFINITY	INFINITY			100	100	
1:	21.48138	2.000000		SK16_SCHOTT	100	100	
2:	-124.10000	5.260000			100	100	
STO:	-19.10000	1.250000		F4_HOYA	100	100	
4:	22.00000	4.690000			100	100	
5:	328.90000	2.250000		SK16_SCHOTT	100	100	
6:	-16.70000	43.050484			100	PIM	
IMG:	INFINITY	0.028933			100	0	

- CCY S1 0;CCY S2 0;CCY S3 0;CCY S4 0;CCY S5 0;CCY S6 0
- THC S0 0;THC S1 0;THC S2 0; THC S4 0;THC S5 0
- GLC S1 0;GLC S3 0
- SUR SA F

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	0	
1:	21.48138	2.000000		620410.603236	0	0	0
GP1: SK16_SCHOTT SPG:				PRC:			
2:	-124.10000	5.260000			0	0	
STO:	-19.10000	1.250000		616589.366156	0	100	0
GP1: F4_HOYA SPG:			PRC:				
4:	22.00000	4.690000			0	0	
5:	328.90000	2.250000		SK16_SCHOTT	0	0	
6:	-16.70000	43.050552			0	PIM	
IMG:	INFINITY	0.028933			100	0	

Coupling variables together

- There are two ways to couple parameters

- Use a pickup
  - This keeps them always coupled

- Use coupling control codes
  - This couples them only during optimization
  - Applies the same change to all coupled variables
  - The parameters only end with the same value if they started out equal

- The preferred method for coupling variables is to use a pickup

Pickups

- A pickup defines a surface value by a relationship to another surface value.
  - Useful for symmetrical systems and double-pass systems

- The relationship is defined as follows
  - (dep. param. on surface j)=(indep. param. on surface k)*A+B

- Command syntax is (A is the scale factor, B is the offset)
  - PIK param Sj [param] Sk [A [B]] ! Default A=1, B=0

- The parameters can be similar or non-similar parameters
  - Default is that parameters are same

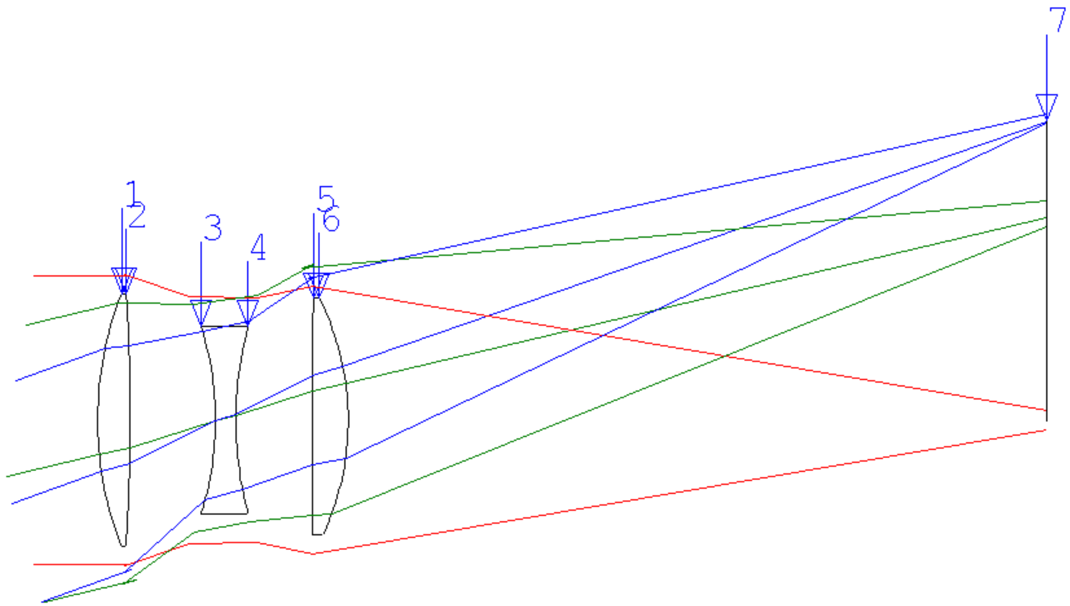
- Examples
  - PIK RDY S3 S1 ! Pickup radius on S3 from S1
  - PIK THI S4 RDY S2 -1 ! Pickup a thickness from a radius
  - PIK PRO S6 S1 ! Pickup a surface profile
  - PIK DEC S3 S1 ! Pickup decenter data

Pickup for glass and change f/no

- PIK GLA S5 S1
- SUR SA F

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	0	
1:	21.48138	2.000000		620410.603236	0	0	0
GP1: SK16_SCHOTT SPG:				PRC:			
2:	-124.10000	5.260000			0	0	
STO:	-19.10000	1.250000		616589.366156	0	100	0
GP1: F4_HOYA SPG:			PRC:				
4:	22.00000	4.690000			0	0	
> 5:	328.90000	2.250000		620410.603236	0	0	PIK
GP1: SK16_SCHOTT SPG:				PRC:			
6:	-16.70000	43.050553			0	PIM	
IMG:	INFINITY	0.028933			100	0	

- FNO 2.8



Check apertures/vignetting

- The lens has apertures on S1 and s5, but these are sized for original Cooke1 lens (f/4.5), not the f/2.8 lens

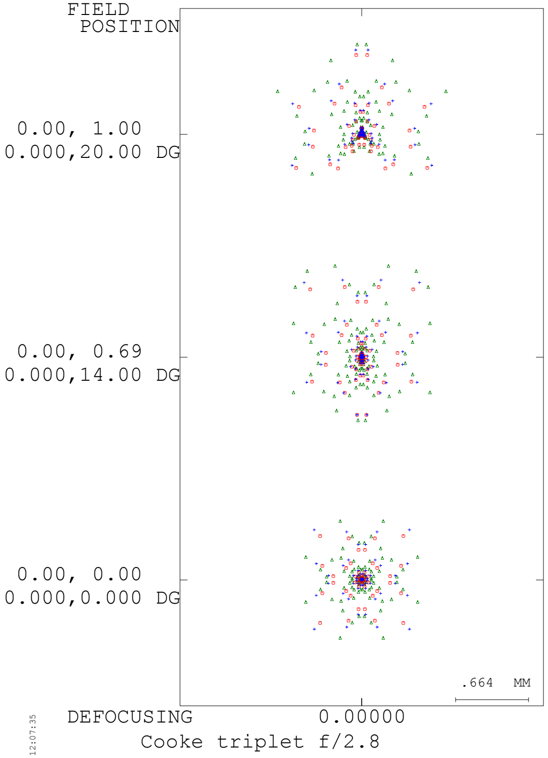
- Since a triplet typically does have vignetting, we will keep the vignetting factors unchanged and delete the apertures

- DEL APE SA
- SPC

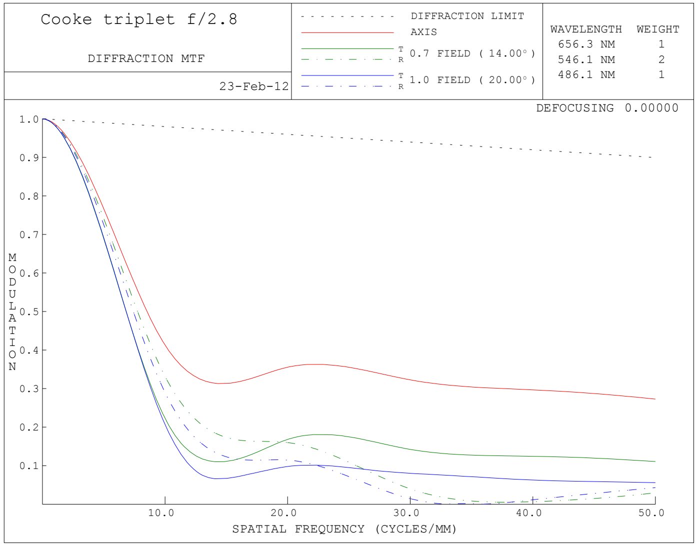
```
SPECIFICATION DATA
   FNO        2.80000
   DIM             MM
   WL          656.30    546.10    486.10
   REF              2
   WTW              1         2         1
   XAN        0.00000    0.00000    0.00000
   YAN        0.00000   14.00000   20.00000
   WTF        1.00000    1.00000    1.00000
   VUY        0.00000   -0.01406    0.16171
   VLY        0.00000    0.06883    0.24355
   POL              N
```

- TIT 'Cooke Triplet f/2.8'

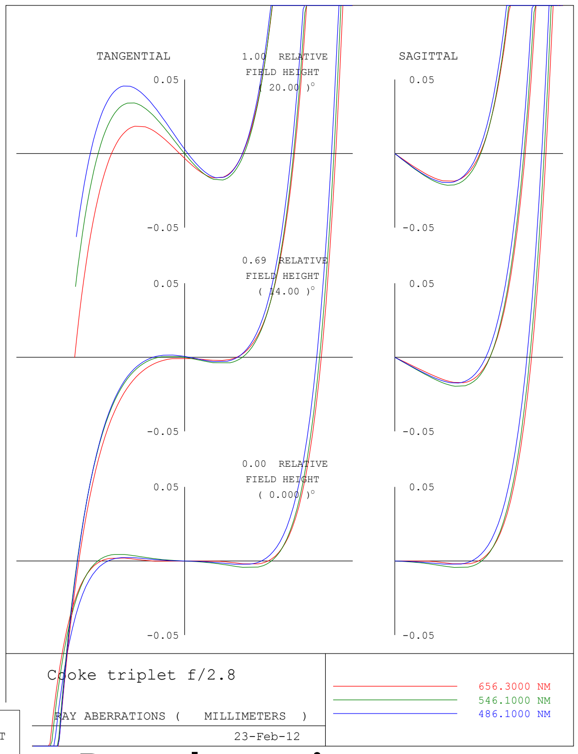
Starting performance



Spot diagram
Scale bar 0.664mm



MTF
MFR 50, IFR 10



Ray aberration curve

AUTO output header

- AUT;EFL=50;VLI IA Y;GO ! VLI – List variables

```
POTENTIALLY ACTIVE SPECIFIC CONSTRAINTS
  EFL                  =        50.000000
```
Requested constraint

```
GENERAL CONSTRAINTS
  MXT       12.000000
  MNT        2.000000
  MNE        2.000000
  MNA        0.100000
  MAE        0.002500
  GLA                  NFK5  NSK16  NLAF2  SF4
```
General constraints

```
ERROR FUNCTION CONSTRUCTION
  WTW        1          2           1
  WTA        0.500000
  DEL        0.385000
  WTX F1     1.000000
  WTX F2     1.000000
  WTX F3     1.000000
  WTY F1     1.000000
  WTY F2     1.000000
  WTY F3     1.000000
```
Error function weights

```
CONVERGENCE CONTROLS
  MXC         25
  MNC          2
  TAR        0.000000
  IMP        0.050000
```
Exit controls

AUTO output header (cont)

```
 VARIABLE LIST

   NO        PARAMETERS *
    1        CUY S1        CUY S2
    2        CUY S2        CUY S3
    3        CUY S3        CUY S4
    4        CUY S4        CUY S5
    5        CUY S5        CUY S6
    6        CUY S6
    7        THI S0
    8        THI S1
    9        THI S2
   10        THI S4
   11        THI S5
   12        THI S7
   13        GLN S1
   14        GLV S1
   15        GLN S3
   16        GLV S3

* Multiple entries on a line are composite variables.
Composite variables are either program-generated bendi
or user-requested couplings.

 16 VARIABLES

 16 CONSTRAINTS CAN BE ACTIVE
```

Requested list of all variables (note program-generated curvature couplings)

This variable (THI S0, infinite thickness)will not be effective)

AUTO output (typical cycle)

```
 Singular variable no.  7 will move only to satisfy constraints.
```
Ineffective variable

```
CYCLE NUMBER 7:

 ERR. F.  =       222.95418348       (change =       -6.95236015)

  X      69.82687233   142.35177197   125.30556214
  Y      69.82687233   170.62668016    90.92479149
```
Error function x,y contribution from each field (and zoom)

```
                  RDY              THI         RMD          GLA
> OBJ:          INFINITY         INFINITY
    1:          22.46445         6.728743              743972.448504
    2:         224.93894         4.810834
  STO:         -37.18578         1.250000              755201.275795
    4:          21.77039         4.917383
    5:          69.77459         4.317205              743972.448504
    6:         -26.81618        38.202791
  IMG:          INFINITY        -0.311001
```
Lens data for this AUTO cycle

```
      EFL          REDU          PIM          OAL          EN PUP       EX PUP
   49.977986     0.000000     38.202791    22.024165    12.020178   -11.035925

 Active Constraints -    6:     target        value        diff         cost
 EFL                     =    5.00000E+01   4.99780E+01  -2.201E-02   7.739E-03
 GL  B  S1                                                            3.888E-04
 GL  C  S1                                                            9.292E-06
 GL  C  S3                                                            1.397E-04
 GL  D  S3                                                            8.627E-04
 Mn  ET  S5                                                          -1.056E-05
    WARNING - Frozen Thickness Violations:
 Mn  CT  S3
```
List of active constraints

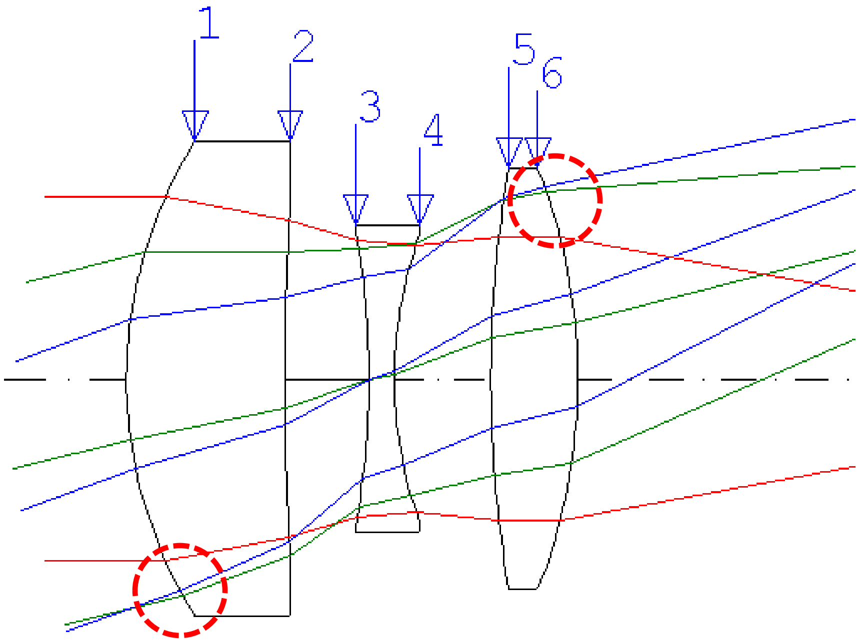
Caused by frozen THI S3 smaller than MNT

Post-optimization apertures and vignetting

- Optimization has used a ray grid based on the vignetting factors
  - Default aperture sizes are based on the vignetted bundle
  - Change S1 and S6 to default circular apertures

    SET APE S1;SET APE S6
  - Set vignetting

    SET VIG



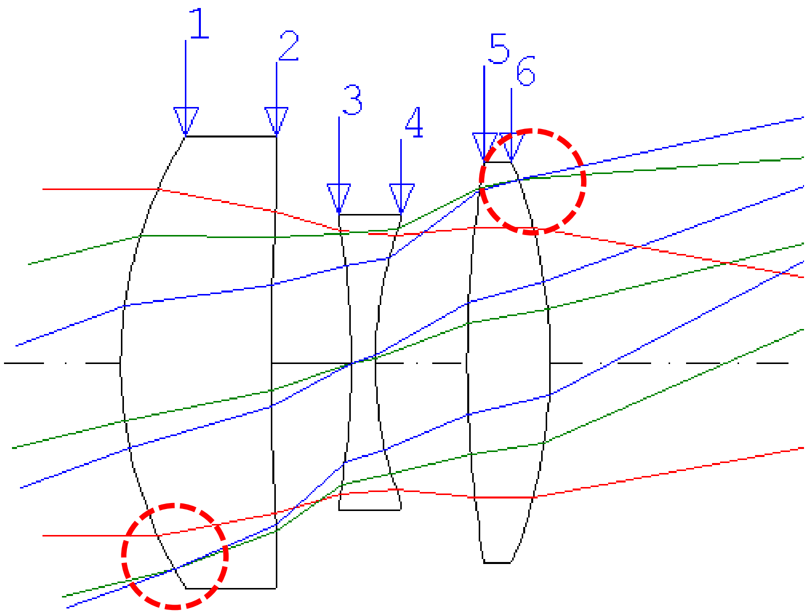
Post-optimization vignetting

- Vignetting factors during optimization

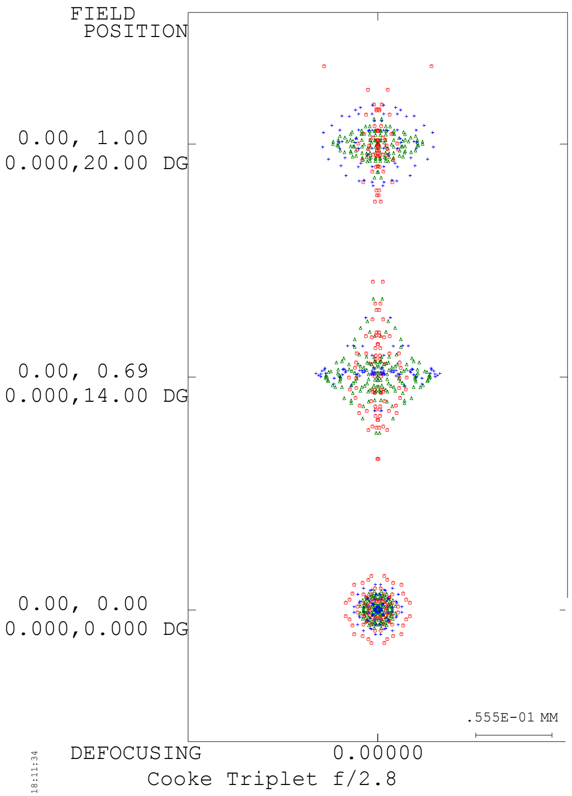
YAN	0.00000	14.00000	20.00000
WTF	1.00000	1.00000	1.00000
VUY	0.00000	-0.01406	0.16171
VLY	0.00000	0.06883	0.24355

- Vignetting factors after applying default apertures

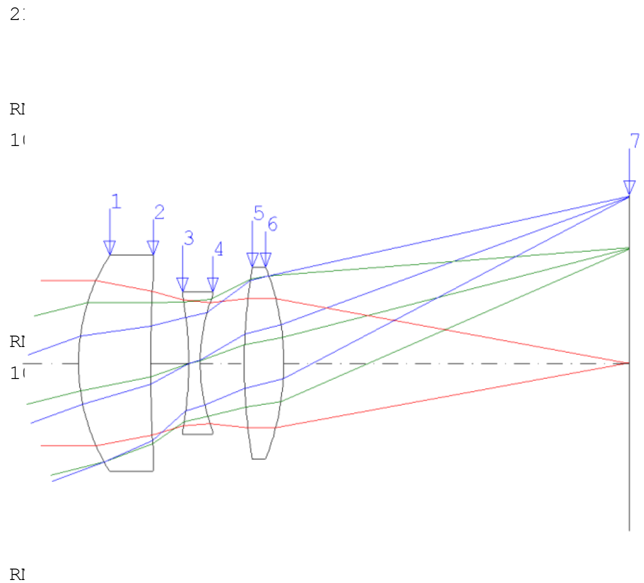
YAN	0.00000	14.00000	20.00000
WTF	1.00000	1.00000	1.00000
VUX	0.00000	-0.00789	-0.01719
VLX	0.00000	-0.00789	-0.01719
VUY	0.00000	-0.04724	0.16171
VLY	0.00000	0.06883	0.20636

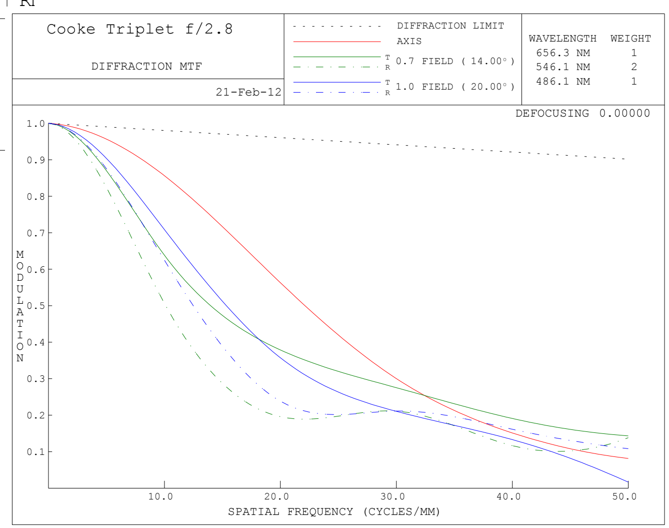


Optimized triplet performance

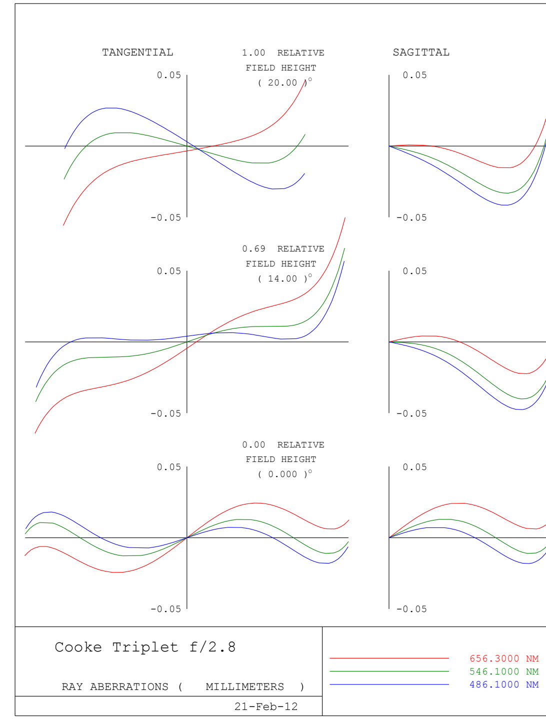


Spot diagram
Scale bar 0.0555mm





MTF
MFR 50, IFR 10



Ray aberration curve

3rd day

Section 13

Reflective systems

Refractive Modes

- **REFR**
  - Standard refracting surface ; ray fails if it encounters a TIR (total internal reflection) condition
  - You do not need to enter this mode (entered automatically)

- **REFL**
  - Standard reflecting surface ; angle of reflection equals angle of incidence

- **TIRO**
  - Total internal reflection only ; ray fails if it encounters a refractive condition

- **TIR**
  - Total internal reflection ; ray refractive or TIRs, depending on conditions
  - Only used on non-sequential surfaces

Refractive Modes

- **RMD Sk REFR | TIR | TIRO | REFL [...z]**
  - Specifies refractive mode change (or zoom) at the selected surface

- Alternatively, you can specify REFL as the glass_name in a GLA command or TIRO as the glass_name in an S command, as shown in the examples below

- Examples
  - RMD S2 REFL : Surface 4 is a reflecting surface
  - RMD S4 TIRO : Surface 4 is a TIRO surface
  - GLA S4 REFL : Surface 4 is a reflecting surface
  - S 16.5 -3.8 TIRO : Use of TIRO with S command

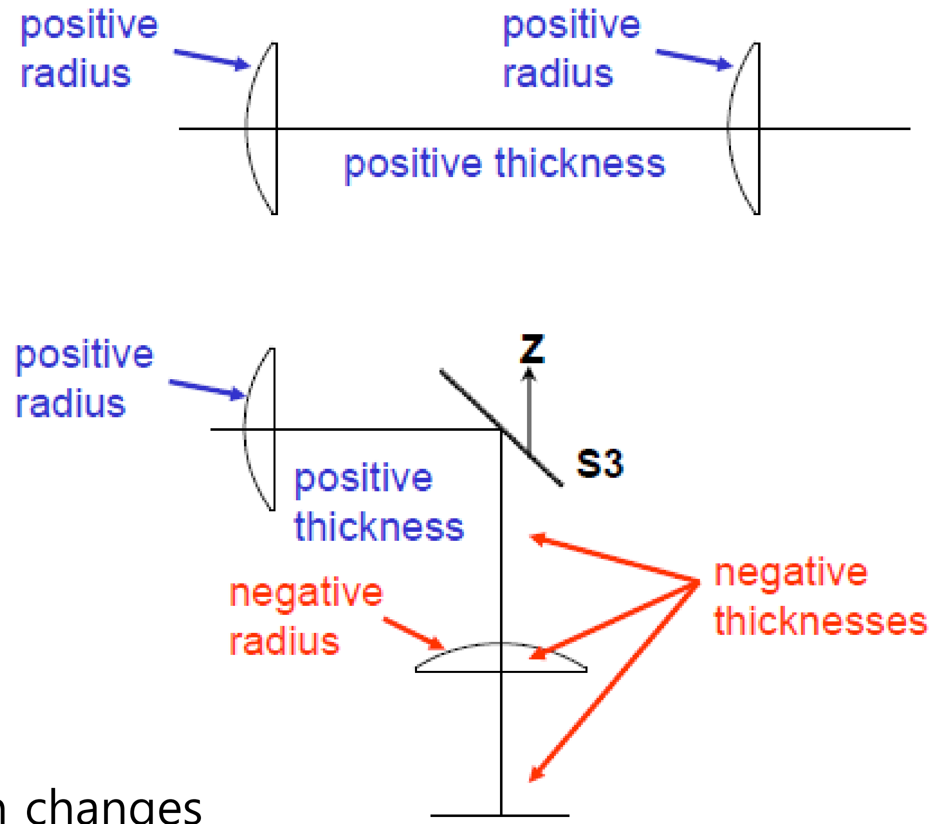
Reflective systems – setup difference

- Most setup is identical to refracting systems

- Important points
  - Signs of thicknesses usually change after each reflection
    - Positive after even number of reflections
    - Negative after odd number of reflections
    - True even for tilted reflectors
  - Never enter negative indices of refraction (handled automatically internally)

- Dummy surfaces and obscurations may be important in reflecting systems

Sign changes after reflection



To make the sign changes
SCA S3..I FAC -1

Section 14

Tilted and decentered systems

Philosophy

- Surfaces in CODE V are always centered on their local coordinate system

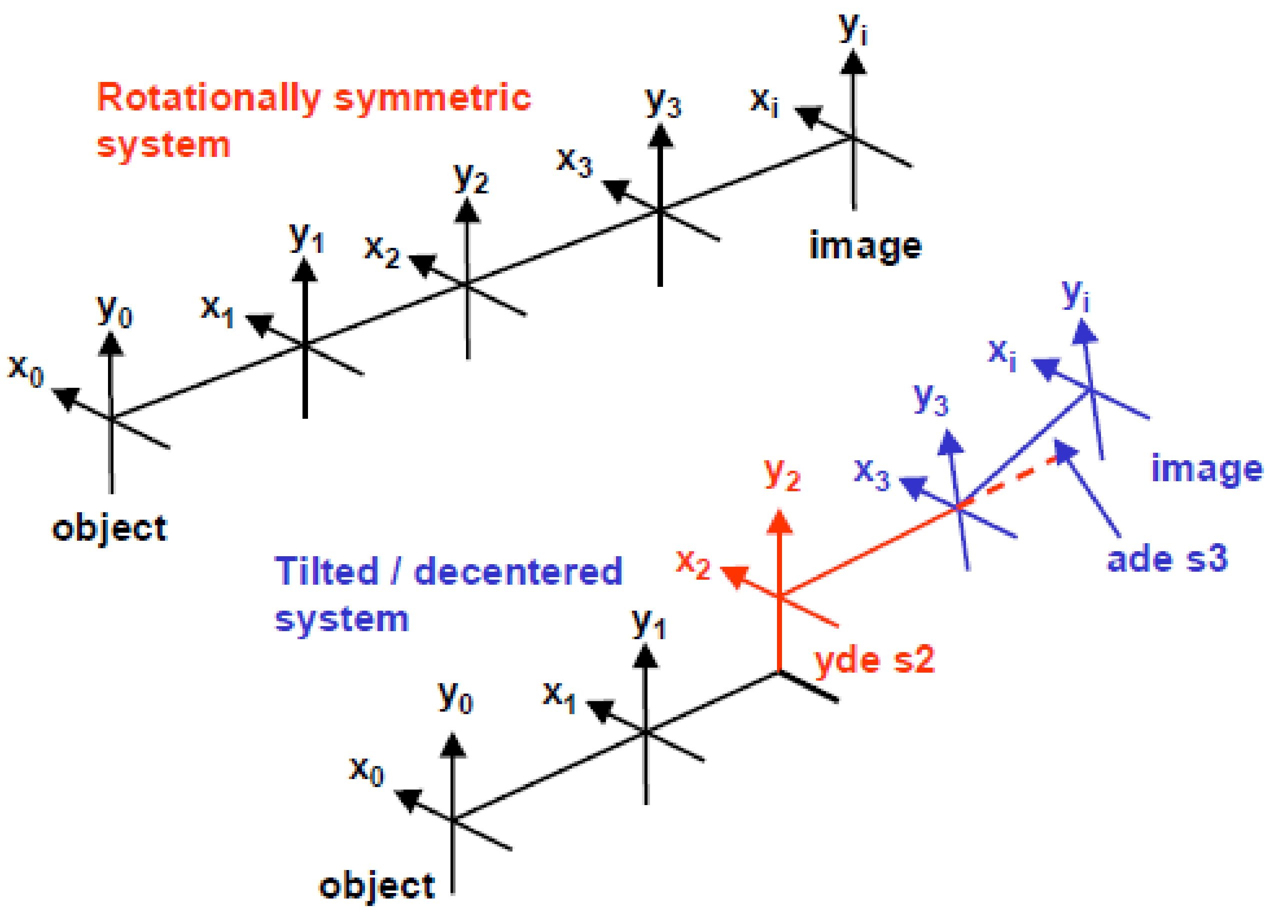
- When we “tilt or decenter a surface”, we are actually tilting or decentering the local coordinate system in which the surface is defined

- The coordinate systems for surfaces following the tilted/decentered surface are aligned to the tilted/decentered system until changed
  - Thus, multiple tilts and decenters are cumulative

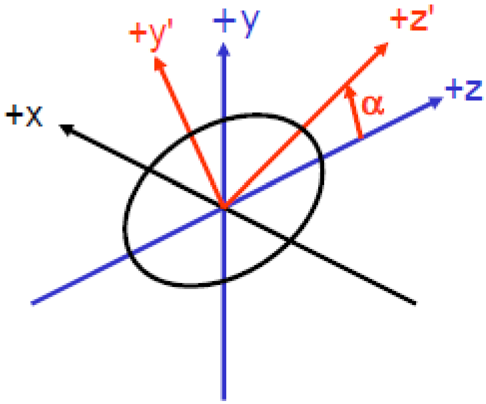
- Thus, the z-axis defines a “mechanical reference axis” which is not necessarily the optical axis

Decentered systems

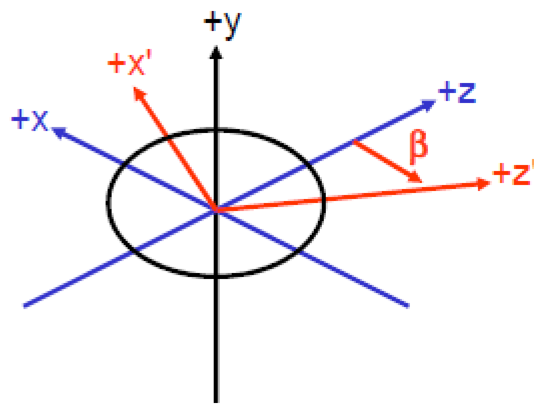
- Each surface has its own local coordinate system



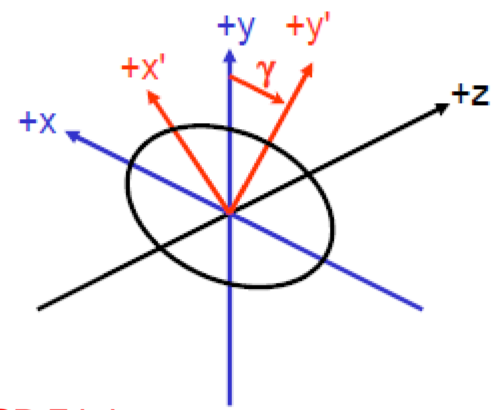
Tilt sign conventions



ADE(α)
Tilt in YZ plane
(about -x axis)
Left handed rotation



BDE(β)
Tilt in XZ plane
(about -y axis)
Left handed rotation



CDE(γ)
Tilt in XY plane
(about +z axis)
Right handed rotation

Take caution with the handedness of α, β

Order of operations

- For basic decenter
  - Translate from previous surface (by THI)
  - Decenter by XDE, YDE, ZDE (order does not matter)
  - Tilt by ADE in coordinate system defined above steps
  - Tilt by BDE in coordinate system defined above steps
  - Tilt by CDE in coordinate system defined above steps
  - Refract, reflect or diffract the ray
  - Translate to next surface (THI) along the z-axis defined by the above steps

- If BEN type decenter, repeat ADE, BDE, CDE tilts before translating to next surface

- If DAR type decenter, return to starting coordinate system before translating to next surface

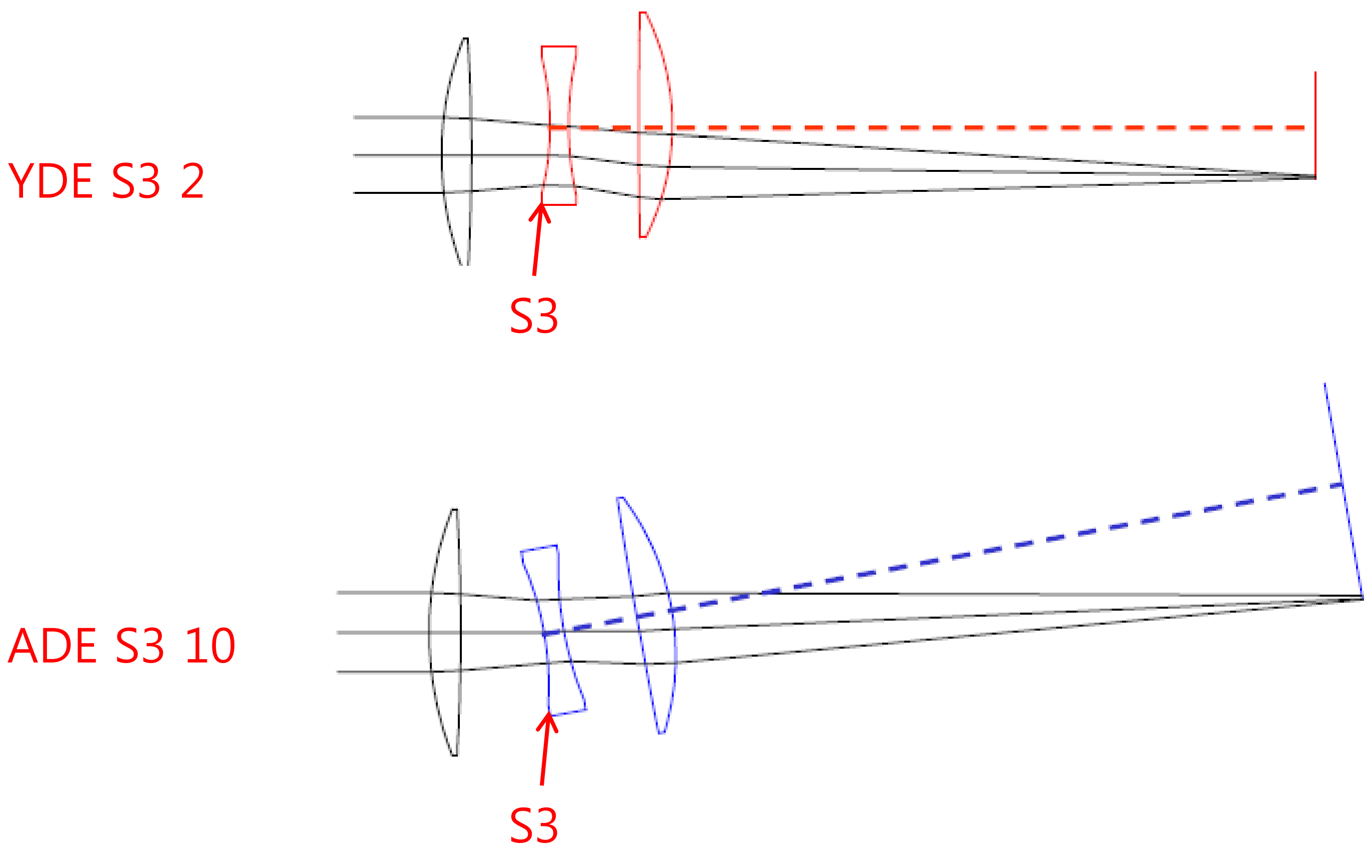
- To alter the order of the above operations, you may need to use multiple dummy surfaces with one operation per surface

Types of decenters

- Basic type (DDA)
  - New axis defined for current and succeeding surfaces
- Decenter and return (DAR)
  - New axis defined for current surface only
- Return (RET)
  - Returns coordinate system to those of a previous surface
- Decenter and bend (BEN)
  - Adds another set of tilts after the current surface
  - Only used on fold mirrors
- Reverse (REV)
  - Defines new axis for succeeding surfaces, but NOT for the current surface
- Global (GLB)
  - Surfaces are oriented globally relative to some specified surface
  - Like a RET plus a Basic DDA

Basic decenter and tilt (DDA)

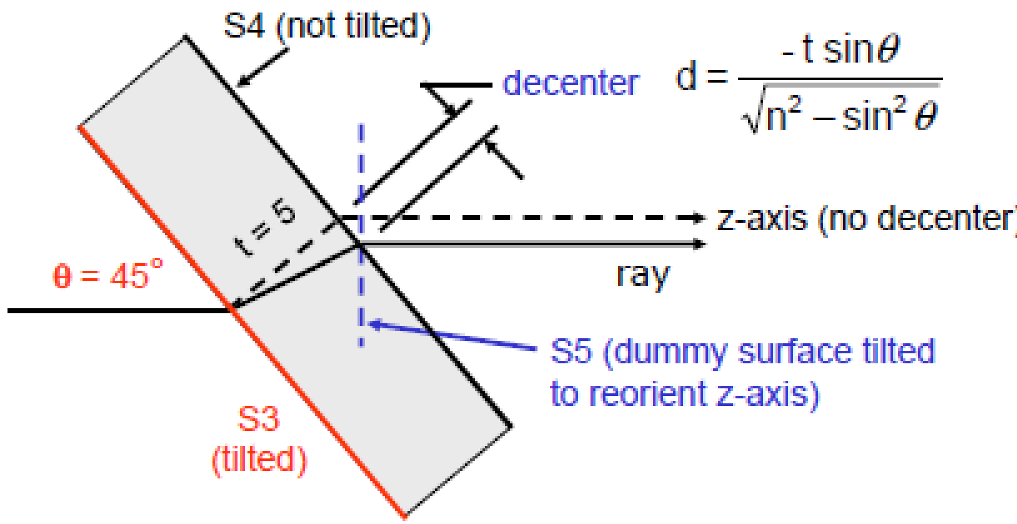
- A new axis is defined for current and succeeding surfaces



Tilted plate

- On axis chief ray does not follow z-axis
  - Requires decenter to align z-axis with ray
  - Requires dummy surface after plate to realign z-axis

S3 0 5 BK7
ADE 45
S4 0 0
S5 0 (thi)
YDE -2.625
ADE -45



Workshop 1

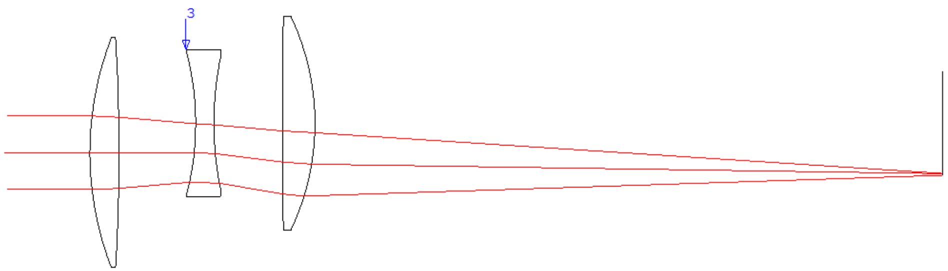
- Making the previous DDA figure using Cooke1.len

RES CV_LENS:Cooke1

FNO 10; YAN 0; STO S1;CIR S3 EDG 5

YDE S3 2

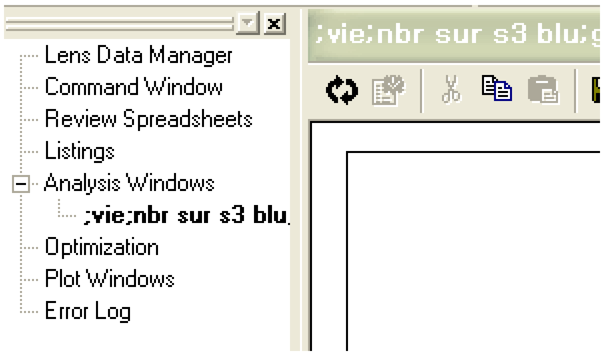
TOW; VIE; NBR SUR S3; GO

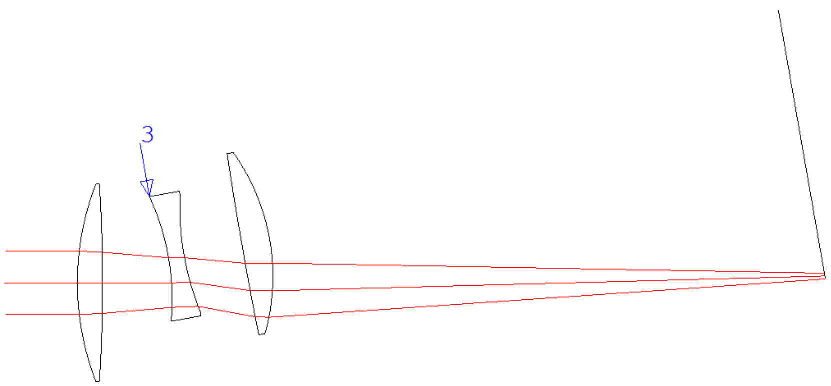


DEL DDA S3

ADE S3 10

Press re-run button

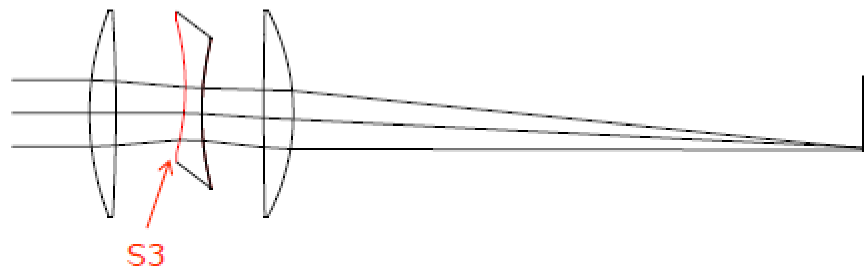




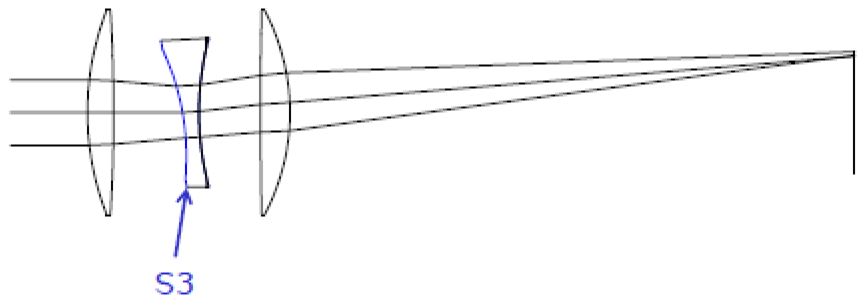
Decenter and return (DAR)

- Only the current surface is tilted and/or decentered
  - Acts as a temporary tilt for just one surface

YDE S3 2
DAR



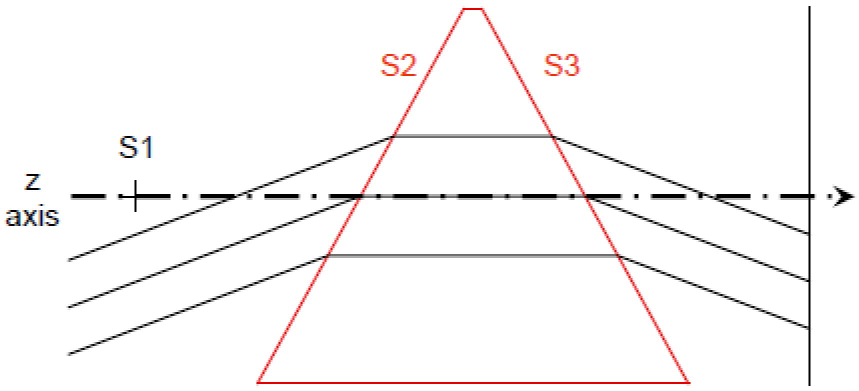
ADE S3 10
DAR



Workshop 2

- Dispersing prism

```
LENS NEW
EPD 2; DIM M; YAN 20; WL 587
S1 0 5;
S2 0 5 LLF6; STOP
! Tilt and return
ADE -30; DAR
! Rectangular aperture
REX 4; REY 4
S3 0 5
! Tilt and return
ADE 30; DAR
! Rectangular aperture
REX 4; REY 4
```



Decenter and bend (BEN)

- Used for convenience in entering fold mirrors
  - Eliminates the need for an extra dummy surface to follow the reflected light
  - Do not use on scanning mirrors (will not keep optics following scan mirror in a fixed location!)

- Adds an additional, equal tilt after reflection

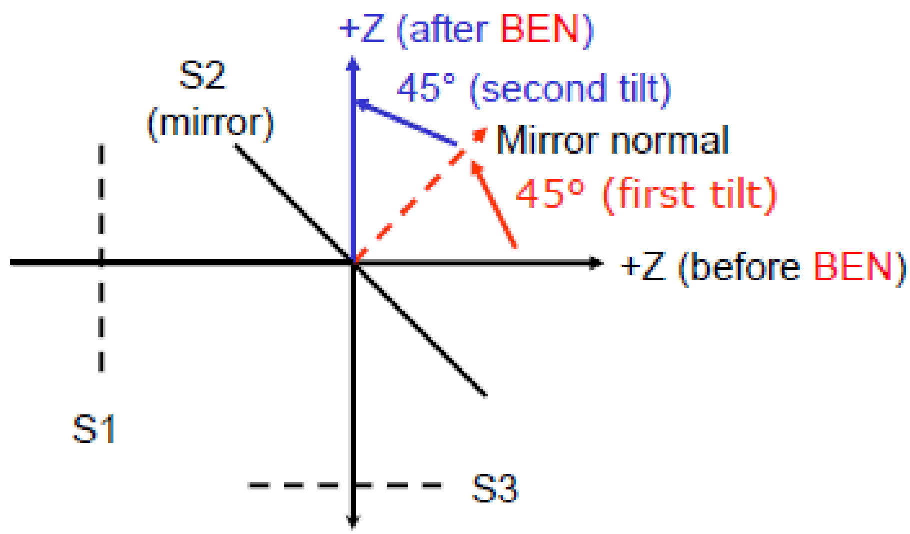
S1 0 10

S2 0 -10 REFL

ADE 45

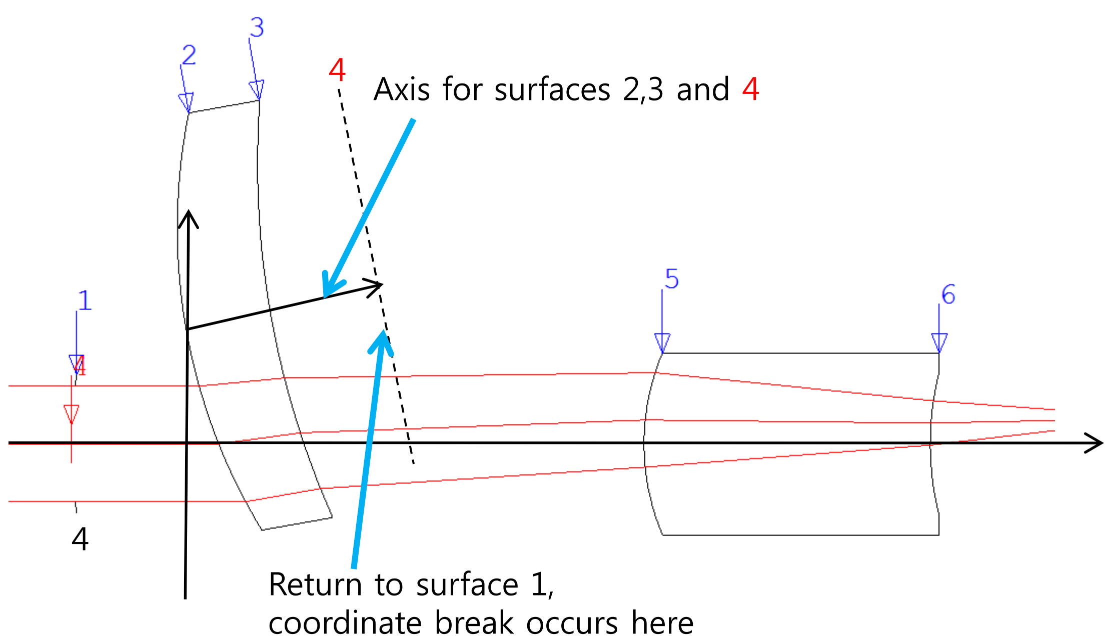
BEN

S3 …



Return to surface (RET)

- Return to the local coordinate system of a prior surface for this segment. Automatically "undoes" cumulative effects of intervening tilts, decenters, and thicknesses
- We recommend that you use this type on a dummy surface



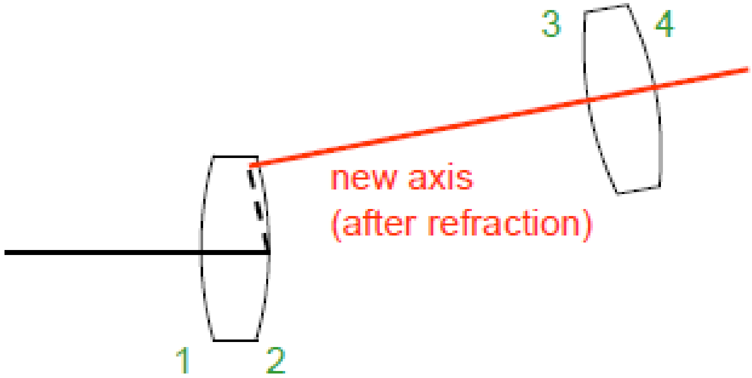
S1 8 2
S2 10 1.5 BK7
ADE 10
YDE 2
S3 15 2
S4 0 10
RET S1
S5 4 5 BK7
S6 5 5
…

Reverse decenter (REV)

- New axis is defined after refraction, reflection, or diffraction at the current surface
  - New axis affects subsequent surfaces, but not the current surface

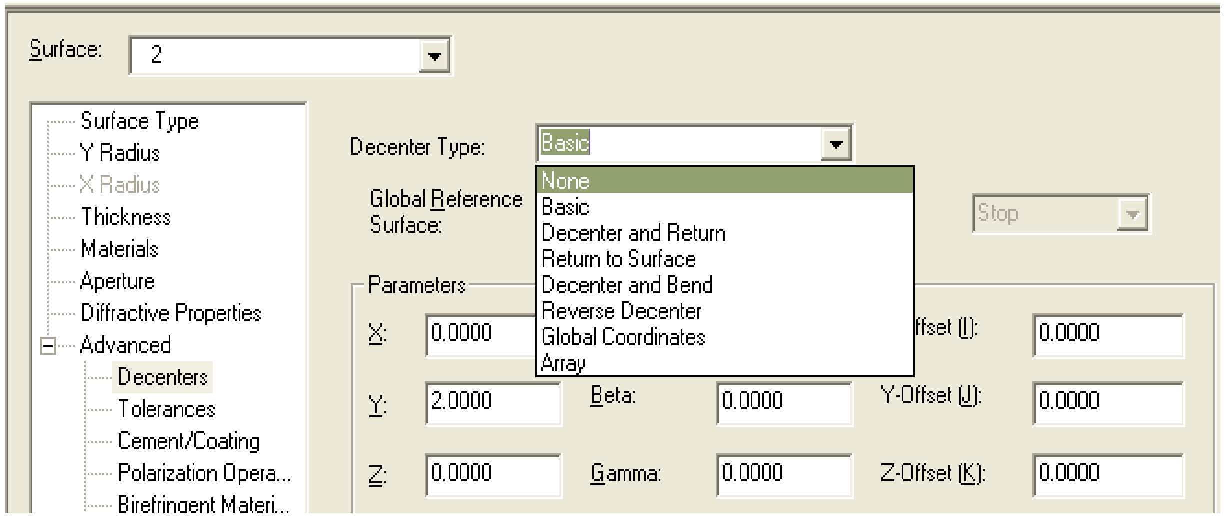
- Order of operations is reversed, and opposite signs are used
  - Tilt by –CDE, then by –BDE, then by –ADE, then decenter by –XDE, -YDE, and –ZDE
  - Designed to allow undoing of a specific basic decenter and tilt
    - RET surface can often be used for same operation

YDE S2 -20
ADE S2 -10
REV



Deleting decenter and tilt data

- In **Surface Properties** dialog box, change **Decenter Type** to **None**



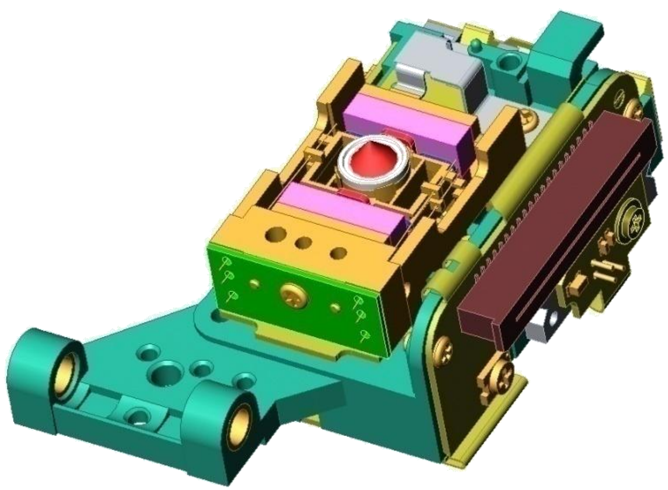
- On command line, use DEL DDA Sk|Si..j (delete decenter data)
  - Can also delete special decenter type (reverts to Basic)
  - DEL DAR, DEL BEN, DEL REV, DEL GLB

Section 15

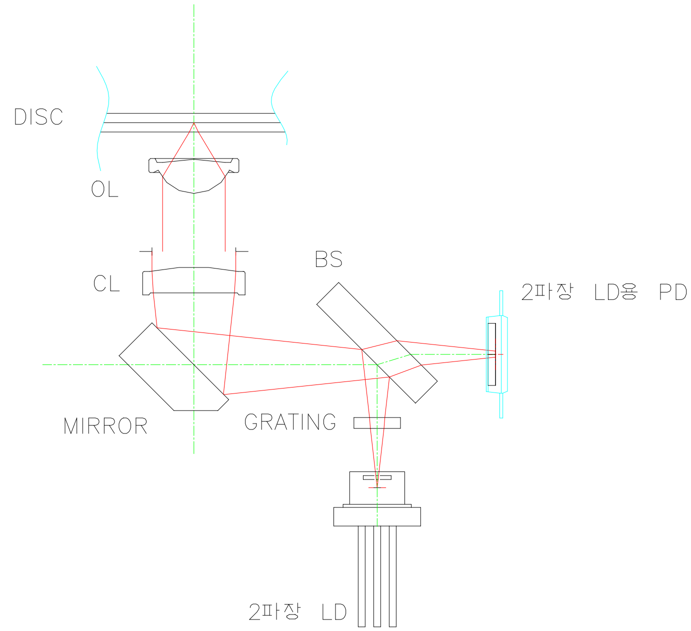
Making your first optical system

Optical pickup system

- Optical pickup is a very good example to learn how to make an optical system(or layout)
  - Making NA 0.6 objective lens
  - Combining a prior collimator lens, f=20mm



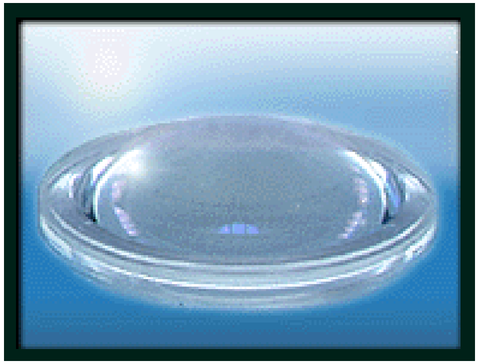
Appearance of the DVD-RW pickup

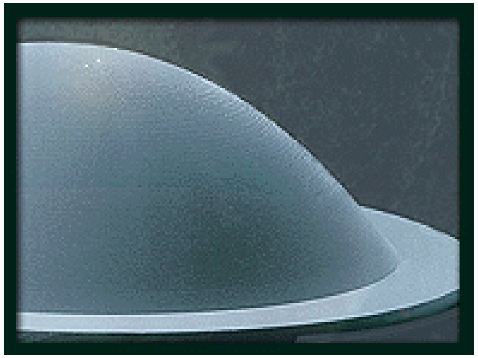


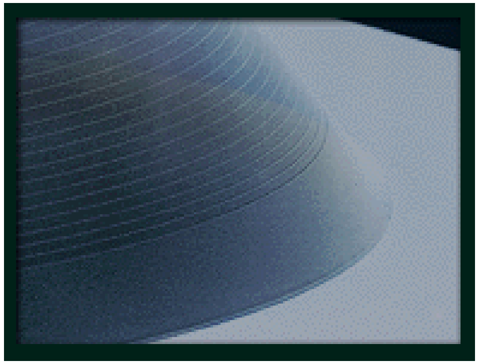
Optical layout of the DVD-Player pickup

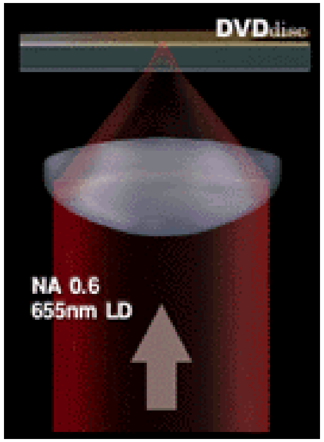
Objective lens for DVD/CD

- The objective lens for DVD/CD player has a diffractive + refractive structure ➔ So, called diffractive lens
  - It's for different wavelength (650nm, 780nm) and NA (0.6, 0.45)
  - We'll just make the DVD only lens for modeling









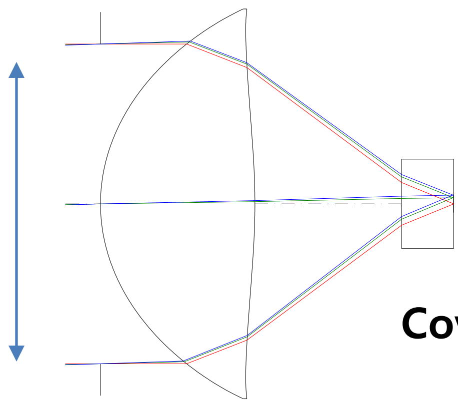
Specification

- Purpose : Objective lens for DVD Player
- Wavelength : 650nm
- Focal length : 3.05mm
- Numerical aperture : 0.6
- Magnification : 0
- Working distance : 1.67mm
- Lens thickness : 1.78mm
- Cover glass : 0.6mm (Polycarbonate)
- Material : APEL (5514ML)
- Surface Type
  - 1st Surface : Aspheric surface
  - 2nd Surface : Aspheric surface
- Design temperature : 25°C
- Image height : 0.1mm

Layout for design

- Use EPD instead of NA(or NAO)

EPD 3.66



Cover glass t0.6(Polycarbonate)

Lens t1.78(APEL)

  - EPD(Entrance pupil diameter)=2 X f X NA =3.66

    LEN NEW
    EPD 3.66
    WL 650
    YIM 0 0.07 0.1

Material data

- IN CV_MACRO:PLASTICPRV
  - Polycarbonate

Private Catalog Name	Name	Source	Defined Wavelength Region	Temperature deg. C	Specific Gravity	Coefficient Thermal Expansion (x1e7 /C)	dN/dT (x1e-6/C)	d, F, C Glass Code
'P-CARBO'	Polycarbonate	[1]	1014 - 365 nm	'room'	1.25	670	-107	585.300
'PCHMAO'	Polycyclohexylmethacrylate	[1]	656 - 486 nm	'room'	1.11	?	?	505.561
'PEIO'	Polyetherimide	[1]	644 - 480 nm	'room'	1.27	560	?	660.186
'PMMAO'	Polymethylmethacrylate	[1]	1014 - 365 nm	'room'	1.18	600	-105	492.572
'P-STYRO'	Polystyrene	[1]	1014 - 365 nm	'room'	1.05	640-670	-140	591.308
'SANO'	Styrene Acrylonitrile	[1]	1014 - 365 nm	'room'	1.07	640	-110	567.348

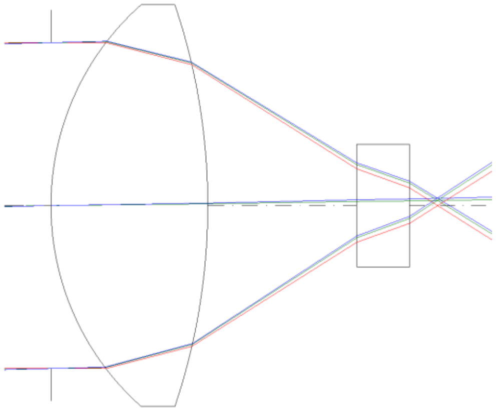
  - APEL

'A5514_10'	APL5514ML	[8]	780 - 404.7 nm	9.7	1.04	600	-	546.563
'A5514_25'	APL5514ML	[8]	780 - 404.7 nm	24.8	1.04	600	-	544.562
'A5514_40'	APL5514ML	[8]	780 - 404.7 nm	39.4	1.04	600	-	543.586
'A5514_55'	APL5514ML	[8]	780 - 404.7 nm	55.1	1.04	600	-	541.567
'A5514_70'	APL5514ML	[8]	780 - 404.7 nm	69.8	1.04	600	-	539.566

Surface data

- Now surface pointer is at the stop surface

```
INS S2..6                 ! Insert surfaces s2..6
CIR S1 (3.66/2)           ! User defined aperture
S2 3 1.78 'A5514_25'      ! RDY 3 for initial value
S3 -7 0.02                ! RDY -7 for initial value
                          ! Distance from lens vertex to flange
S4 0 1.67
S5 0 0.6 'P-CARBO'        ! Cover glass
PIM                       ! Solver for first order layout

TOW;VIE;GO                ! Drawing lens
```



First order data

CODE V> FIR

INFINITE CONJUGATES

EFL	4.1373 ← Target : 3.05mm
BFL	1.2053
FFL	-3.7677
FNO	1.1304

CODE V> IND

REFRACTIVE INDICES

GLASS CODE	650.00
'A5514_25'	1.541433
'P-CARBO'	1.580296

EFL optimization

ASP S2; ASP S3	! Make S1 and S2 aspheric
S2	! Move surface pointer to S2
CCY 0; KC 0; AC 0; BC 0; CC 0; DC 0	! Make variables
S3	! Move surface pointer to S3
CCY 0; KC 0; AC 0; BC 0; CC 0; DC 0	! Make variables

SUR S2..3 F

```
             RDY             THI      RMD        GLA            CCY    THC    GLC
 2:        2.00000        1.780000          'A5514_25'          100    100
   ASP:
   K   :    0.000000   KC :        0
   CUF:     0.000000   CCF:      100
   A   :0.000000E+00   B   :0.000000E+00   C   :0.000000E+00   D   :0.000000E+00
   AC :        0       BC :        0       CC :        0       DC :        0

 3:       -7.00000        0.020000                              100    100
   ASP:
   K   :    0.000000   KC :        0
   CUF:     0.000000   CCF:      100
   A   :0.000000E+00   B   :0.000000E+00   C   :0.000000E+00   D   :0.000000E+00
   AC :        0       BC :        0       CC :        0       DC :        0
```

AUT; EFL=3.05;imd=0; GO

1st result

- WAV;GO

FIELD			BEST INDIVIDUAL FOCUS				BEST COMPOSITE FOCUS			
	FRACT	DEG	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL	SHIFT (MM.)	FOCUS (MM.)	RMS (WAVES)	STREHL
X	0.00	0.00	0.000000	0.001619	0.0096	0.996	0.000000	0.000010	0.1424	0.449
Y	0.00	0.00	0.000000				0.000000			
X	0.00	0.00	0.000000	0.000007	0.0833	0.760	0.000000	0.000010	0.0833	0.760
Y	0.70	1.31	0.000515				0.000515			
X	0.00	0.00	0.000000	-0.001699	0.1525	0.399	0.000000	0.000010	0.2124	0.169
Y	1.00	1.88	0.000675				0.000703			

  - The RMS wavefront is good in general, but its image-height performance isn't fit for optical storage

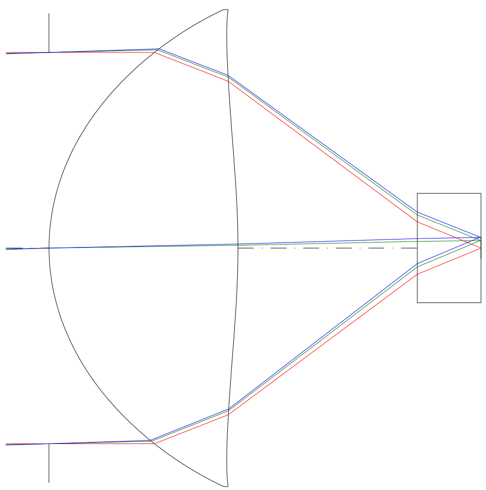
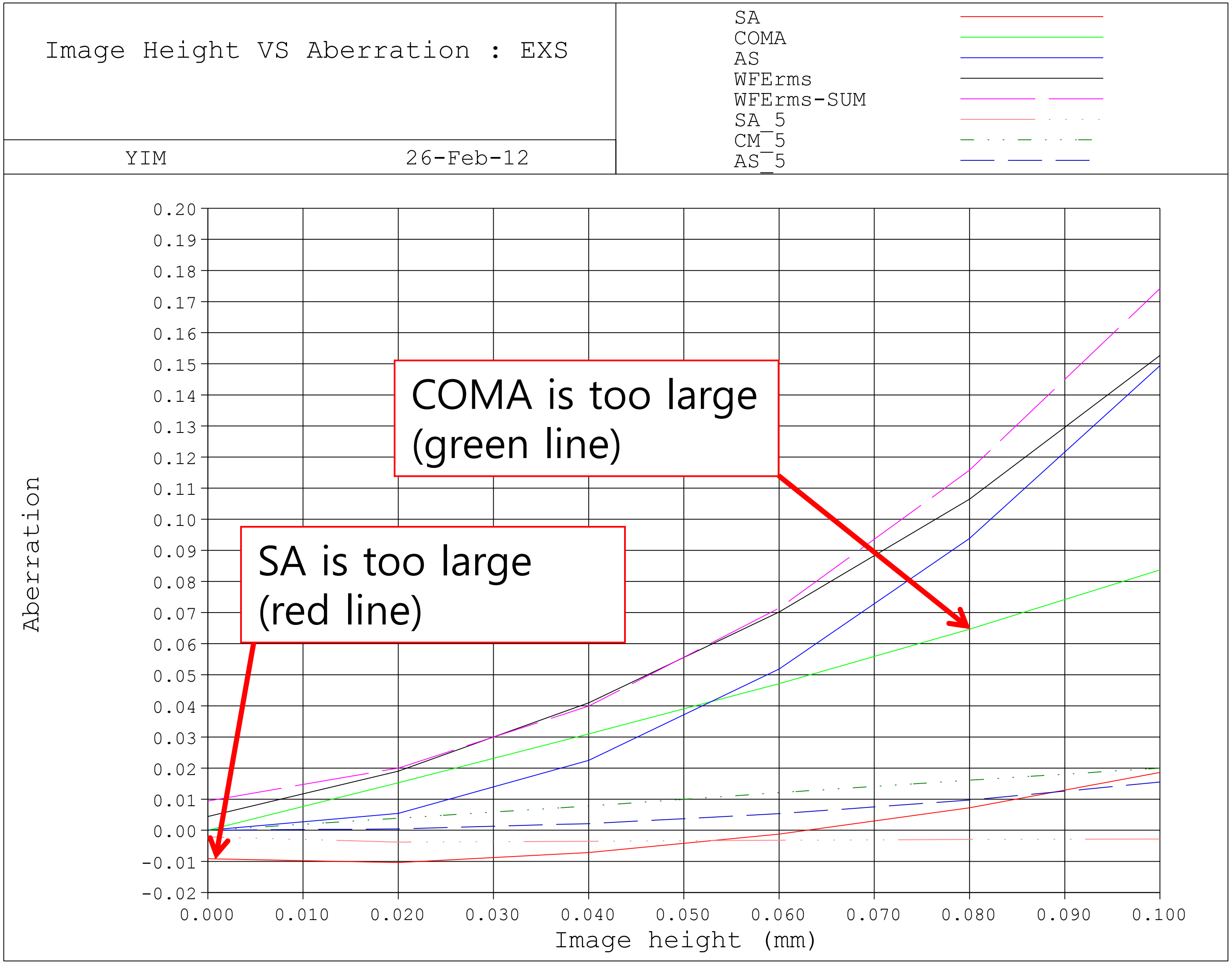


Image-height performance



2nd optimization

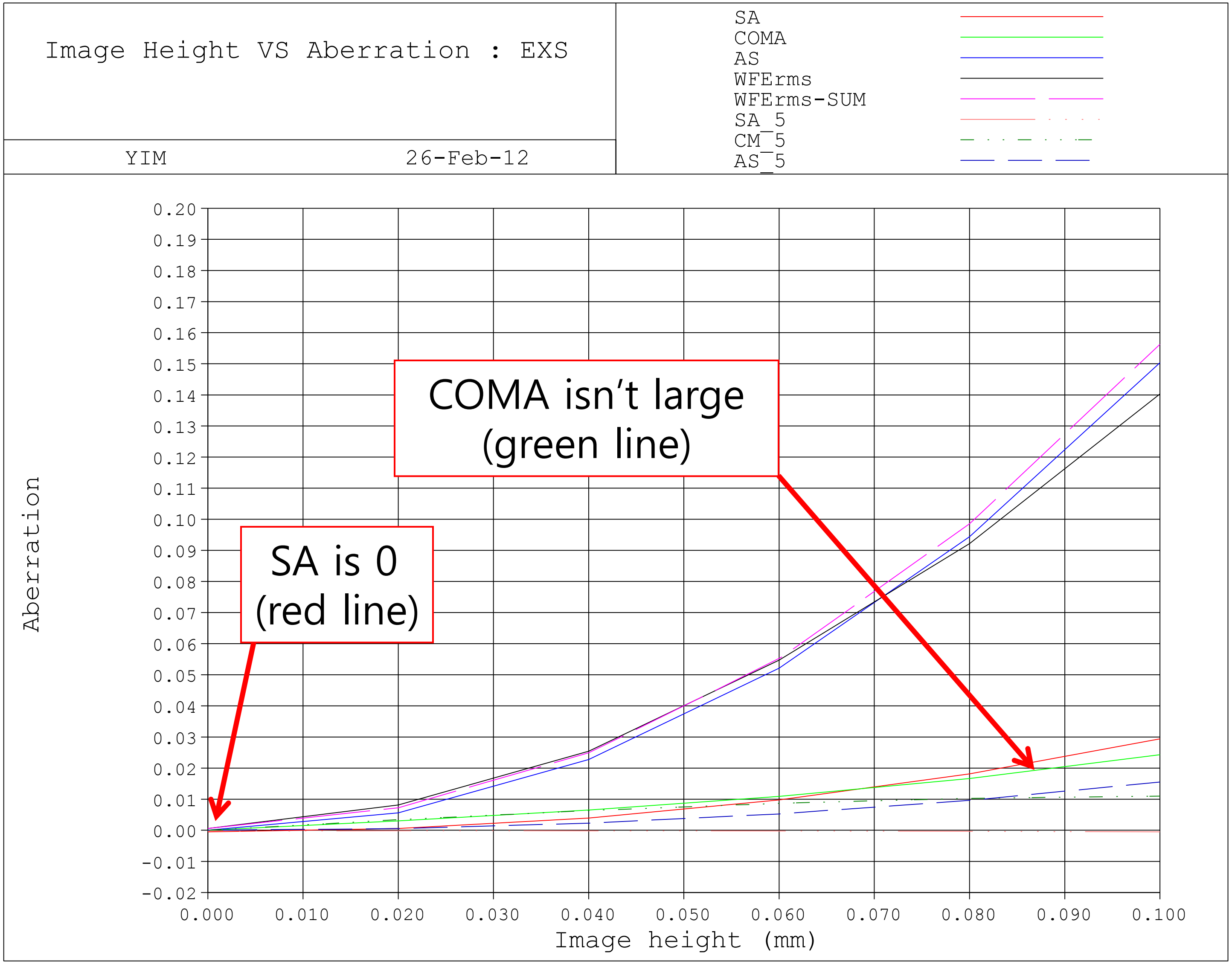
- WTF 20 2 1
- AUT; EFL=3.05; IMD=0; IMP 0.00001; MXC 500; GO
- WAV; GO

```
FIELD                         BEST INDIVIDUAL FOCUS                          BEST COMPOSITE FOCUS
    FRACT     DEG        SHIFT      FOCUS       RMS      STREHL        SHIFT       FOCUS       RMS      STREHL
                         (MM.)      (MM.)     (WAVES)                  (MM.)       (MM.)     (WAVES)

X   0.00      0.00     0.000000   0.000029    0.0008     1.000       0.000000   -0.000245   0.0244     0.977
Y   0.00      0.00     0.000000                                      0.000000

X   0.00      0.00     0.000000  -0.001619    0.0698     0.825       0.000000   -0.000245   0.1385     0.469
Y   0.70      1.31     0.000400                                      0.000407

X   0.00      0.00     0.000000  -0.003339    0.1401     0.461       0.000000   -0.000245   0.3040     0.026
Y   1.00      1.88     0.000510                                      0.000561
```

- SUR S2..3

```
              RDY              THI         RMD          GLA
 2:         1.94523         1.780000                 'A5514_25'
  ASP:
  K  :    -0.669978
  CUF:     0.000000
  A  :0.527600E-02    B  :-.404795E-03    C  :0.191057E-03    D  :-.373578E-04

>  3:        -7.41796         0.020000
  ASP:
  K  :   -84.089204
  CUF:     0.000000
  A  :0.375431E-02    B  :-.103522E-02    C  :0.238059E-04    D  :0.114952E-04
```

Image-height performance



From LD to disc

- Restore CL_20mm.len

  DEL PIM

  THI SO (THI SI-1)

  FLY S1..i-1 ! Flip S1..i-1

  THI SS 5

  YAN 0

  NAO 0.125

  INS S1;INS S3..5

  THI S5 5; THI SO (THI SO)-5

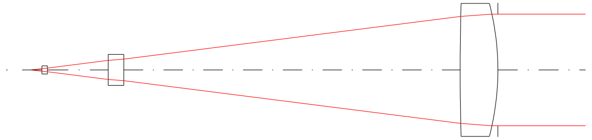
  THI S6 10; THI SO (THI SO)-5

  THI S4 0.7;GLA BK7;THI S2 0.25 !0.25 cover glass, 0.7 grating

  THI S1 0.48;THI SO (THI SO)-0.48 !0.48 LD chip~cover glass

  THI S3 (THI SO);THI SO 0

  TOW;VIE:GO



From LD to disc

- COP SA SI E:₩CVUSER₩IntroCodeV₩OL

  ! Copy surfaces from OL.lens / A prior made objective lens

  STO S11

  SET NAO ! NAO=0.09145

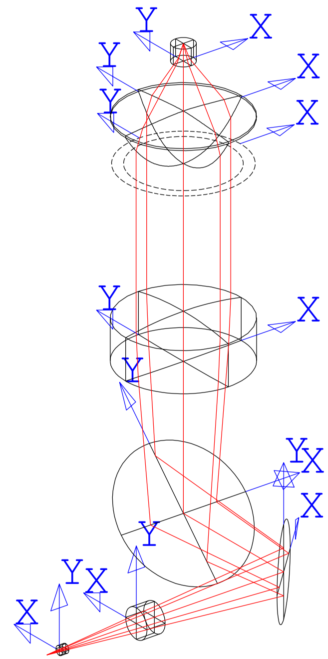
  INS S7; THI S6 5; THI S7 5

  S6; BDE 45; BEN; GLA REFL; THI -5 ! Reflection surface for BS

  S7; ADE 45; BEN; GLA REFL; ! Reflection surface for mirror

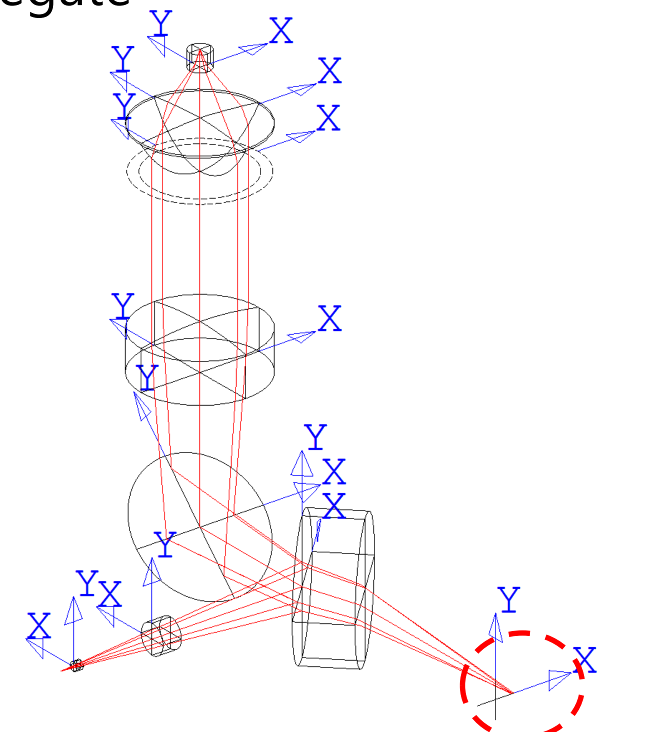
  VIE; VPT S1 -37.8 26.6; LCO BLU; GO

  PIM



From disc to PDIC

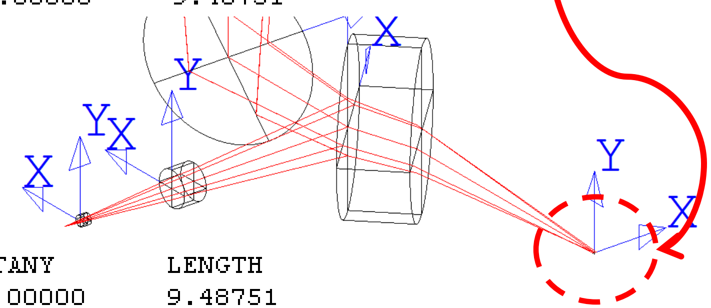
- COP S8..17 S18 * FNY ! Flip and negate
  GLA S17 REFL
  INS S27..32
  THI S27 -5
  S28; ADE -45;BEN ;GLA REFL; THI 5
  S30; BDE -45;GLA BK7;THI 1.9
  RET S32 S29
  VIE; VPT S1 -37.8 26.6; LCO BLU; GO



RSI R1 F1 SI

	X	Y	Z	TANX	TANY	LENGTH
IMG	0.63419	0.00000	0.00000	0.00000	0.00000	9.48751
		OPD =	0.000 Waves			

XDE S33 (X R1 F1 SI)

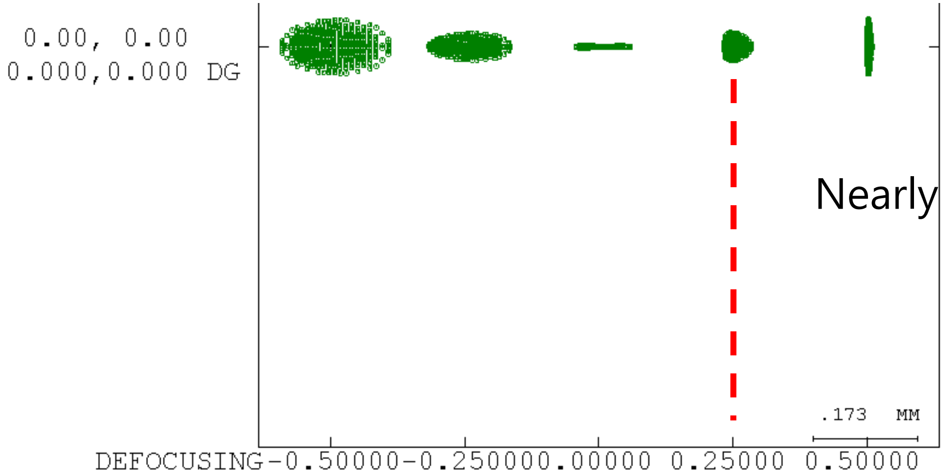


	X	Y	Z	TANX	TANY	LENGTH
IMG	0.00000	0.00000	0.00000	0.00000	0.00000	9.48751
		OPD =	0.000 Waves			

PDIC location

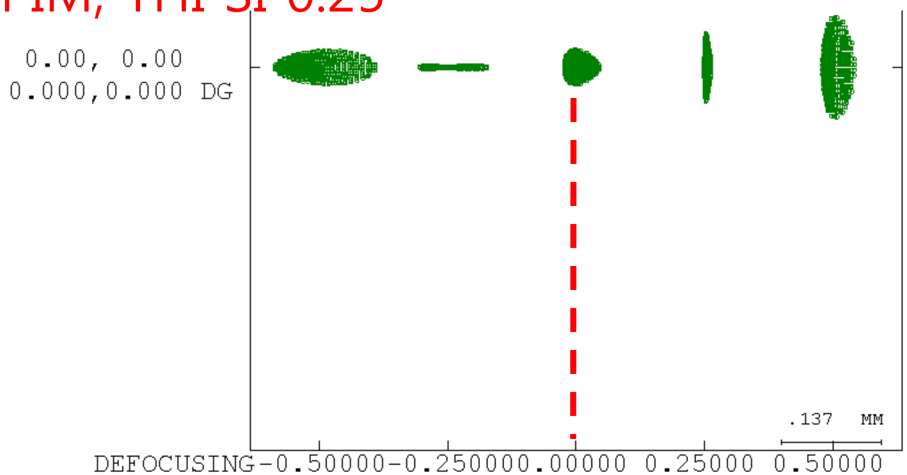
- NFO 5; IFO 0.25; FFO -0.5 ! Defocus

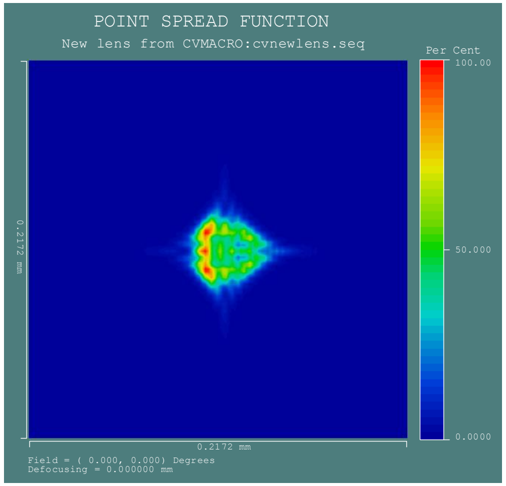
  TOW; SPO; ANN SPO NO; ANN RMS NO; GO



Nearly circular at 0.25mm

DEL PIM; THI SI 0.25





Remind

- INS Sk|Si..j [y_rad_curv thickness [glass_name]]
  - Always inserts the surface(or surfaces) ahead of the specified surface; for example INS S3 will insert a new surface 3 and will make the old surface 3 the new surface 4. The INS command also automatically moves the surface pointer to the inserted surface.

- COP Sk|Si..j Sn [* | filespec [FLX|FLY|NEG|FNX|FNY] [final_thickness]]
  - Copy surfaces Sk|Si..j in source lens, inserting ahead of Sn in current lens
  - * : Current lens
  - FLX,FLY : Flip source lens surfaces about X or Y axis
  - NEG : Negate (scale by -1) for matching to current lens light direction
  - FNX,FNY : Flip and negate

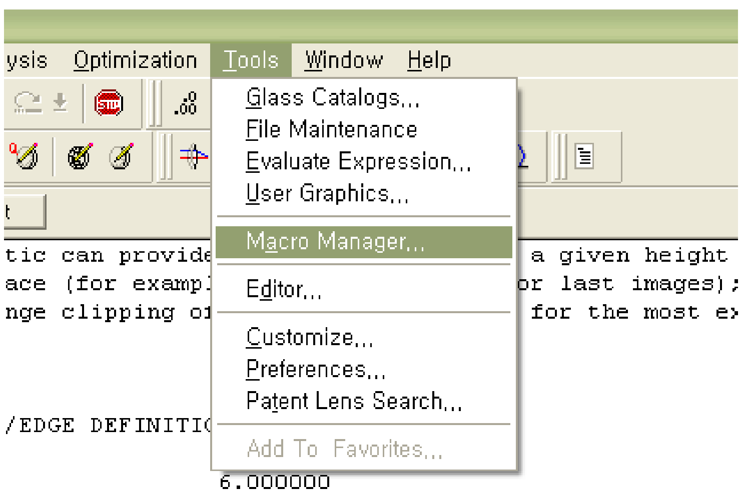
Section 16

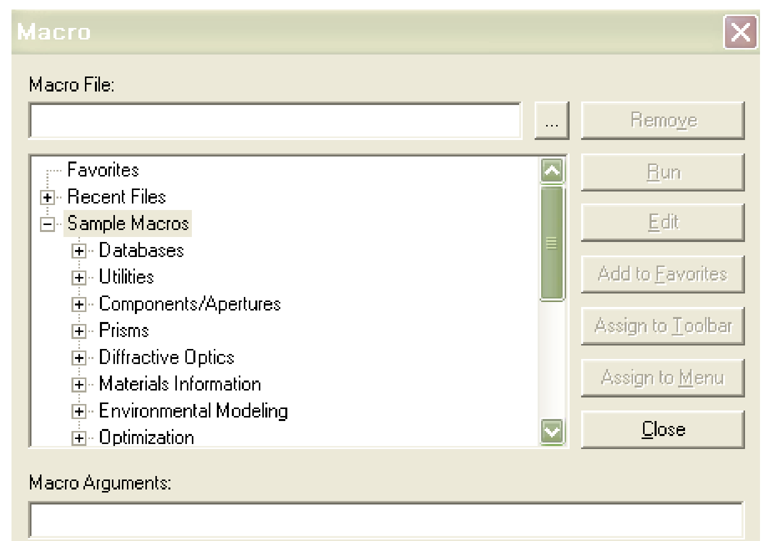
Macros

Macros

- CODE V includes a large number of supplied macros that expand the basic capabilities
  - Macros are written in command-based Macro-PLUS

- Macros are used through a dialog box launched from the **Tools>Macro Manager...** menu
  - Also available from the command line (IN command)



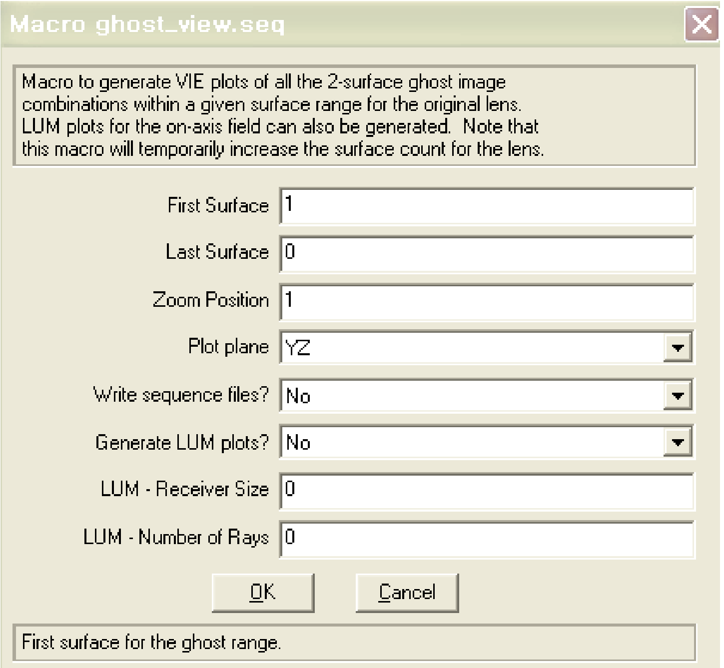


Integrated Macros

- Some macros have been integrated into the user interface as standard features
- These include macros for user-defined tolerancing, inserting various prisms, and distortion grid plotting
- Removing or changing certain macros in the CV_MACRO: directory may disable some program features (please don't)

Macro input dialog boxes

- When you launch a macro from the macro dialog box, it will display its own input dialog box if one is defined for it
  - The dialog box is defined in specially formatted comments in the macro source code
  - These comments are interpreted at run time to build the dialog box
  - The dialog is not created if you run a macro from the command line with the IN command



Macro-PLUS

- Macro-PLUS is a versatile programming language built into CODE V
  - It is used to extend and automate the capabilities of CODE V, as shown in ORA supplied macros
  - It is available anywhere within CODE V
  - Direct access to lens database and ray trace quantities
  - Allows interaction with external text files
  - Allows the use of an expression wherever CODE V expects a number

Macro sequences

- Macro sequences are simply text files containing a sequence of CODE V commands you wish to run
  - These are often called sequence files(.SEQ files), although all macros are actually text files with the file extender .SEQ
  - These text files are created and modified with the CODE V Editor or with any other text editor or word processor (ASCII text only)

- For example : MYMTF.SEQ

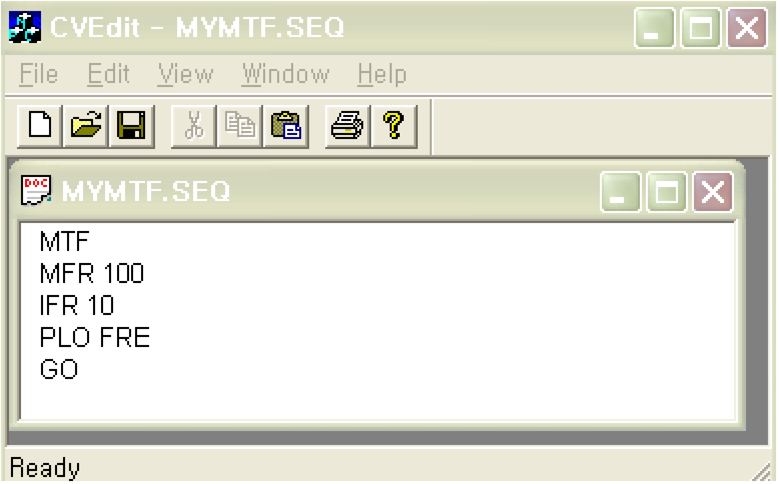
  MTF

  MFR 100

  IFR 10

  PLO FRE

  GO



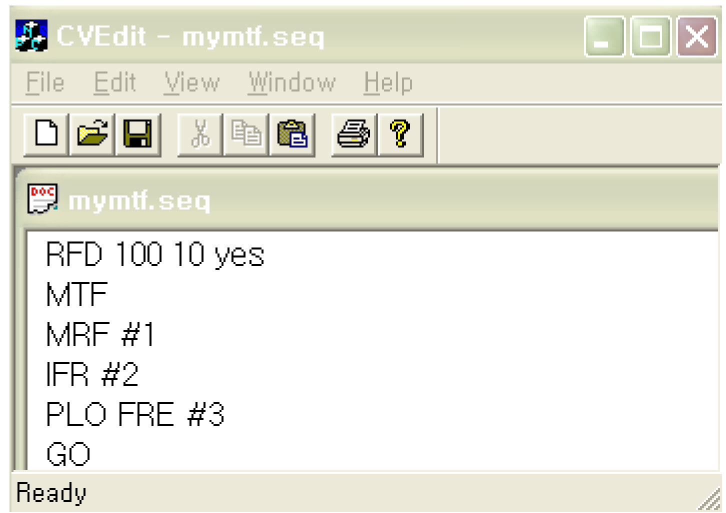
- Execute the macro with the IN command or from Tools>Macro Manager...
  - CODE V> IN MYMTF

Parameter substitution

- When you run a macro with IN, you can pass parameters to the macro
  - This requires the use of parameter inputs in the macro
  - RFD command (replacement field default) can specify parameter defaults

- Example : MYMTF.SEQ

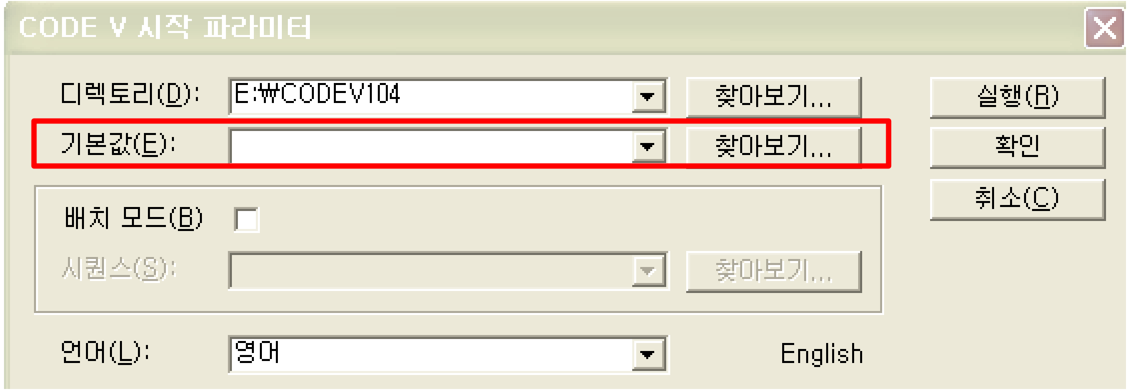
  RFD 100 10 YES
  MTF
  MFR #1
  IFR #2
  PLO FRE #3
  GO



- Execute with or without parameter substitution
  - IN MYMTF 200 20 N ! Uses input values
  - IN MYMTF 200 ! Defaults for #2 and #3
  - IN MYMTF ! Defaults for all parameters

Workshop

- Making “default.seq” file
  - Every time CODE V is started, it runs the default.seq file specified in the Startup Parameters window : **CODE V setup**



  - Useful for
    - Specifying default parameters (units, radius mode, plot settings, glass catalog search order)
    - Setting paths
    - Defining global variables (^pi, ^deg2rad)
    - Calling macro function definitions

Default parameters

- Default parameters allow you to establish settings for all lenses

- Examples
  - RDM NO ! Use curvature mode, not radius mode
  - DDM M ! Set default dimensions to mm
  - DIN 'ORA' ! Designer initials
  - CSO OHARA SCHOTT SPECIAL ! Change order for searching glass
  - VER ALL NO ! Don't echo macro or sequence commands

Setting paths

- CODE V first checks in your current directory for any lenses, macros, .mul or .int files that you reference
- If the file isn't found there, it searches the directories specified by the current path (PTH) command for that type of file
  - PTH LEN CV_LENS: E:₩CVUSER₩EDU
  - CV_LENS: and CV_MACRO: are aliases that point to the "lens" and "macros" directories of the version of CODE V currently running. They allow your defaults.seq file to be independent of CODE V version
- Up to 10 directories can be specified for each
  - PTH LEN ! .len and .mul files
  - PTH SEQ ! .seq files
  - PTH INT ! .int files

Useful entries

- Global variables
  - Constants

    GBL NUM ^pi ^deg2rad

    ^pi == 4*atanf(1)

    ^deg2rad == ^pi/180.0

  - Very useful since CODE V's trigonometric functions use radians, but tilts and ray trace output use degrees

- Define any commonly used functions
  - IN CV_MACRO:FIFTHDEF ! Defined @FIFTH, for 5th order

    ! aberration calculations

mydefault.seq

```
GBL NUM ^pi ^deg2rad
^pi == 4*atanf(1)
^deg2rad == ^pi/180.0
DIN      "YIM"
DDM M
PTH LEN CV_LENS:
PTH SEQ CV_MACRO:
EVA (CD)
```

```
run "E:₩CVUSER₩mydefault.seq"
CODE V> DIN  "YIM"
CODE V> DDM M
CODE V> PTH LEN CV_LENS:
CODE V> PTH SEQ CV_MACRO:
CODE V> EVA (CD)
    (CD) = "E:₩CODEV104"
?ddm
    DDM = MM
?din
    DIN = YIM
eva (^pi)
    (^PI) = 3.14159265358979
eva (^deg2rad)
    (^DEG2RAD) = 0.01745329251994
```

! Current directory : CD