CODE V Introductory Tutorial

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Tutorial Outline

- Introduction to CODE V
- Optical Design Process
- Code V Design Examples :
    1. Digital VGA Camera Objective
    2. 10X Microscope
- Advanced Applications
- References

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Introduction to CODE V

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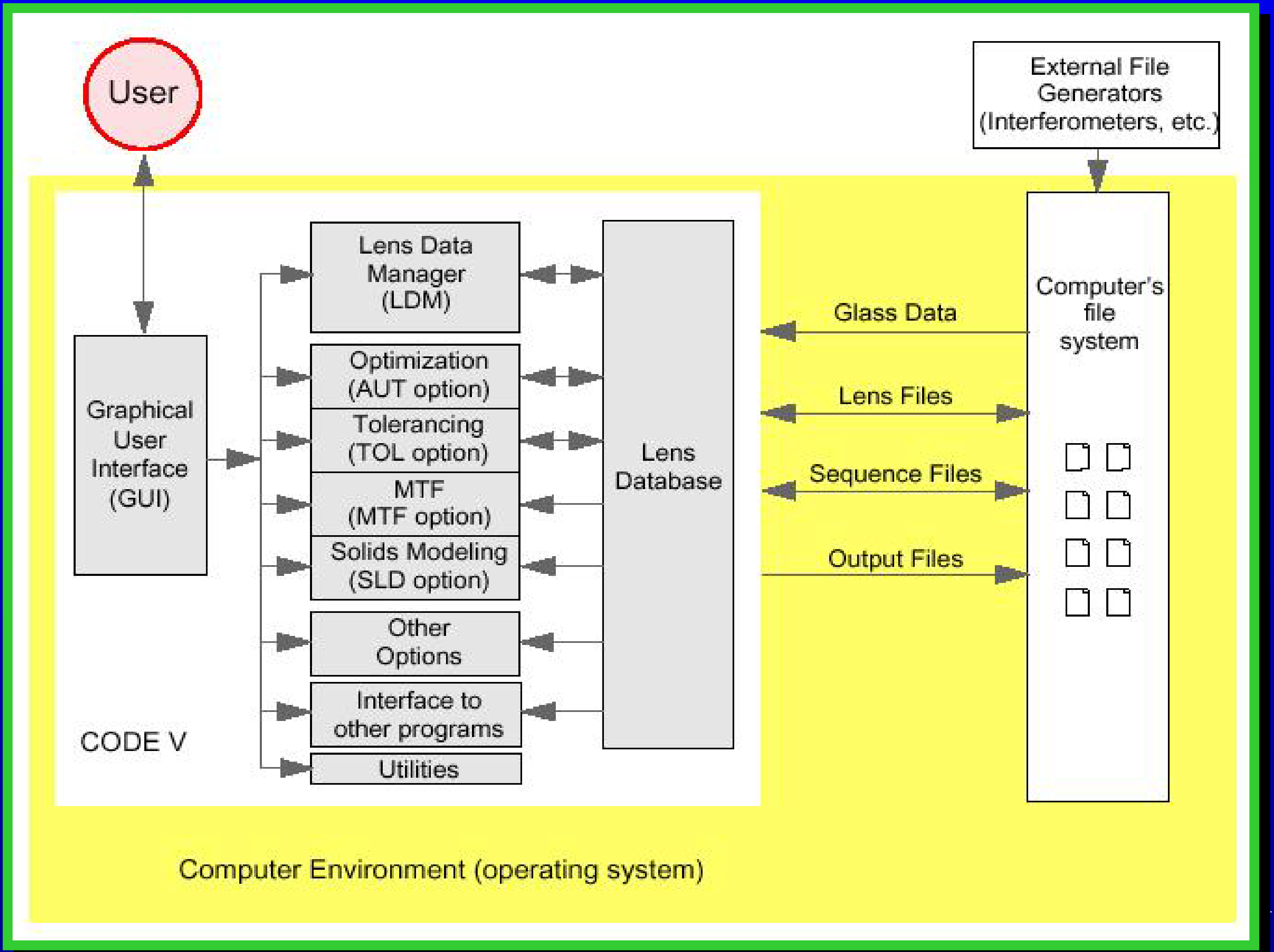
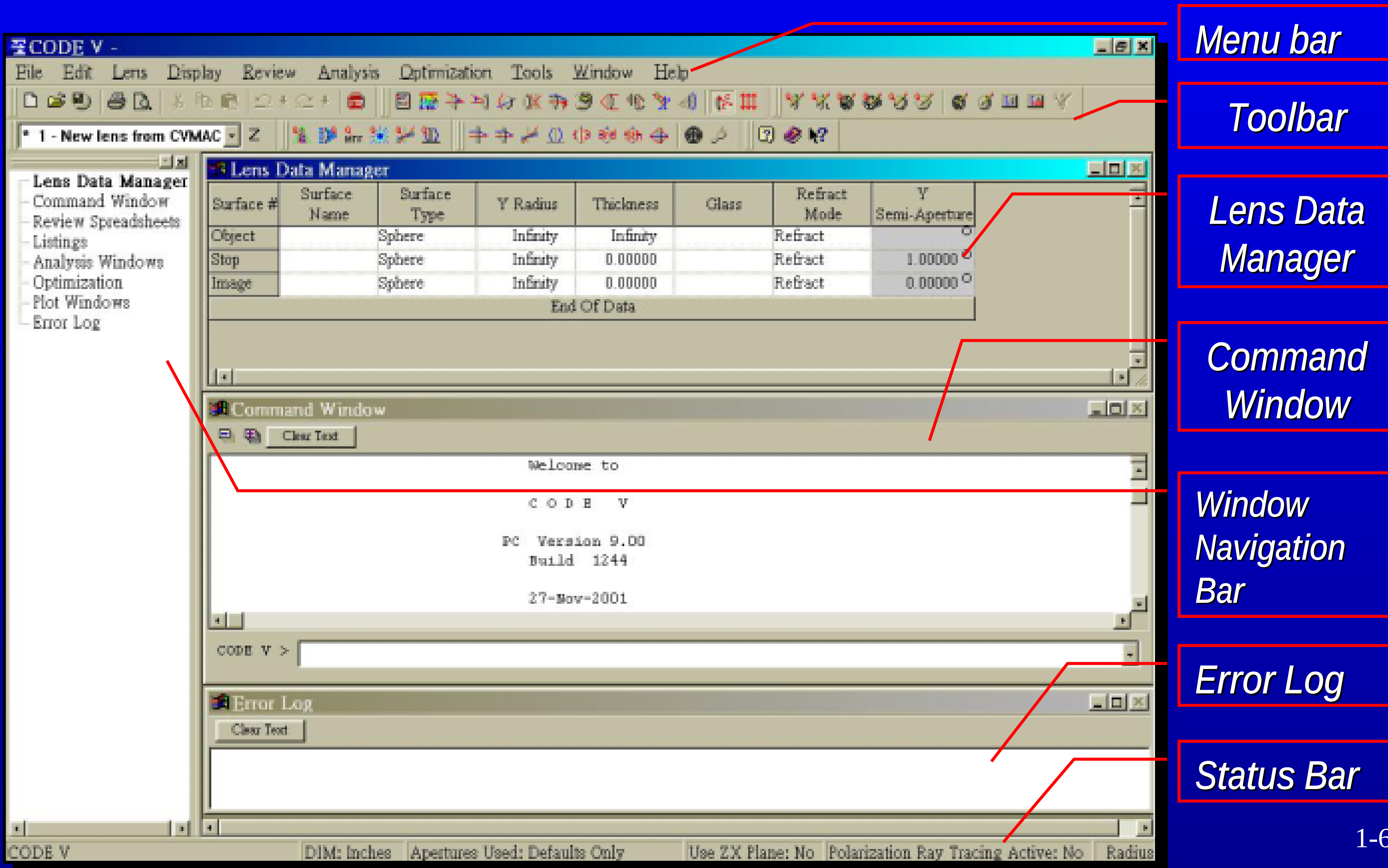
An Overview of CODE V Features

Lens Entry and Editing (database)	Design Functions	Diagnostic Functions	Evaluation Functions	Fabrication and Other Functions
• Spreadsheet data entry • Command entry • Macro language • Solves • Zoom lenses • Decentered and tilted systems • Glass catalogs • IR/UV materials • Special surfaces (Aspherics, Toroids, Gratings, HOEs, "Black Box" modules, user-defined, non-sequential, and many more) • Gradient Index • Full lens data (Optical, Mechanical, Tolerances, Coatings)	• Ray or wave-based error function • MTF optimization • User-defined optimization • Exact control of constraints • User-defined constraints • Global Synthesis • Test plate fitting • Cam design for zoom lenses • Multilayer film design	• Paraxial ray trace • Real ray trace • Aberration plot • Gaussian beam • Third-order aberrations • Higher-order aberrations • Polarization analysis • Astigmatism • Distortion • Pupil map • Field map • Biocular FOV • Catseye plot	• PSF and LSF • MTF (Diffraction based, Geometrical, vs. focus or freq.) • Spot diagrams • RMS wavefront • Encircled energy • Partial coherence • Biocular analysis • Transmission • Narcissus analysis • Ghost images • Illumination analysis	• Tolerancing (MTF/RMS, Distortion, Prim. aberr.) • Lens drawings (Designer use, Elements, Components, 3D Views, Solid models) • Footprints • Cost estimates • Weight • Alignment of built systems • Environmental analysis • Spectral analysis • Image simulation • Interfaces to: - NASTRAN - Interferometers - CAD/CAM via IGES - *LightTools*

Structure of CODE V



CODE V Version 9.00



Optical Design Process

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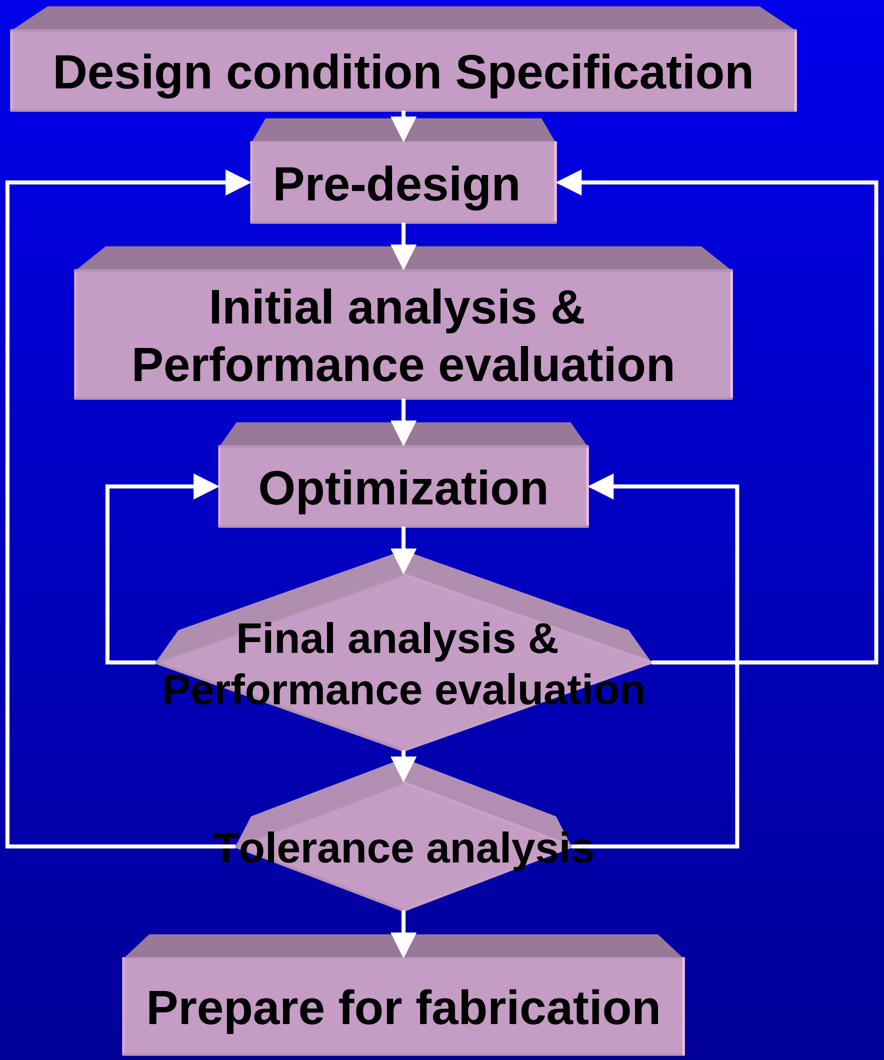
Optical Design Flowchart

- Today's tutorial will based on this process



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Design Example （1）： Fixed-focus VGA Digital Camera Objective

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Outline

- Fixed-focus VGA Digital Camera Objective specification
- Identification of a Starting Point
  - First-order optics consideration
- Selecting a Suitable Starting Point
  - Code V New Lens Wizard
- Perform a Basic Analysis
  - Compare with the specifications: Spot Diagram, Aberration curves, MTF output…..
  - Guideline for Optimization
- Optimization
  - Make things better, Performance re-evaluation
- Tolerance Analysis
  - Prepare for fabrication
- Summary and References

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Identification of a starting point

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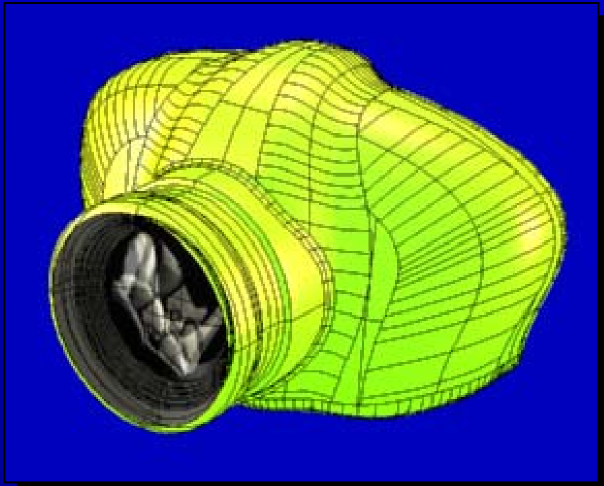
Lens Specifications



Fixed-focus VGA Digital Camera Objective Specifications	
*** Small unmber of elements (1-3) made from common glasses or plastics**	
*** Image sensor (baseline is Agilent FDCS-2020)**	
Resolution	*640 x 480 effective pixels*
Pixel size	*7.4 x 7.4 microns*
Sensitive area	*3.55 x 4.74 mm (full diagonal 6 mm)*
*** Objective Lens**	
Focus	*Fixed, depth of field 750 mm to infinity*
Focal length	*Fixed, 6.0mm*
Geometric Distortion	*< 4%*
F/number	*Fixed aperture, F/3.5*
Sharpness	*MTF through focus range (central area is inner 3 mm of CCD)*
	Low freq. 17 lp/mm: > 90% (central), > 85% (outer)
	High freq. 51 lp/mm: > 30% (central), > 25% (outer)
Vignetting	*Corner relative illumination > 60%*
Transmission	*Lens alone, > 80% 400-700 nm*
IR filter	*1 mm thick Schott IR638 or Hoya CM500*

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Identification of a Starting Point

- From specification directly:
  - 3-element system
  - Effective focal length = 6 mm
  - F/number = 3.5

- First-order calculation:
  - Field of view
  - FOV = 26.5 °

•Starting point scheme

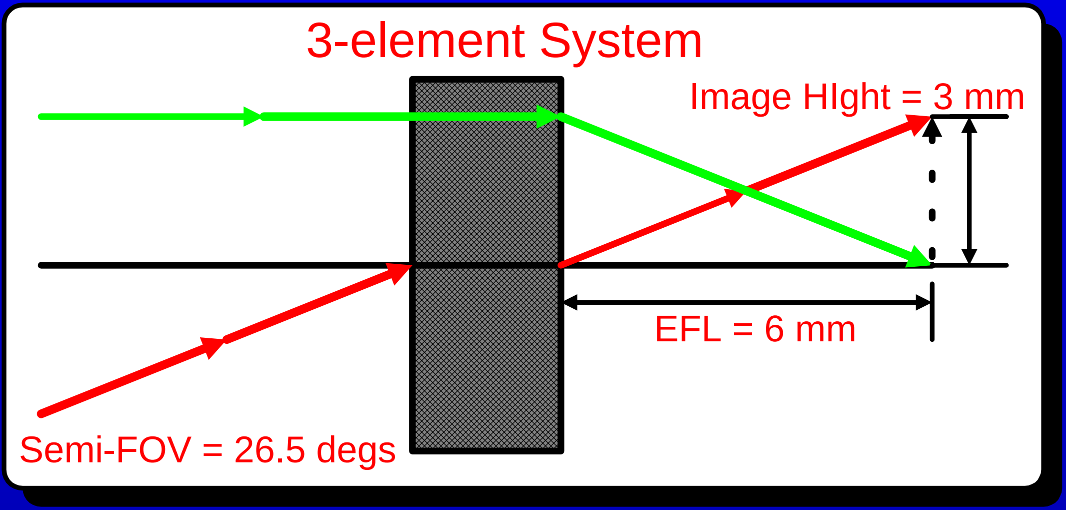

Image height = EFL* tan(semi-FOV)

• These are useful to be a " filter " (criterion) for searching exiting designs in Code V new lens wizard

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Selecting a Suitable Starting Point

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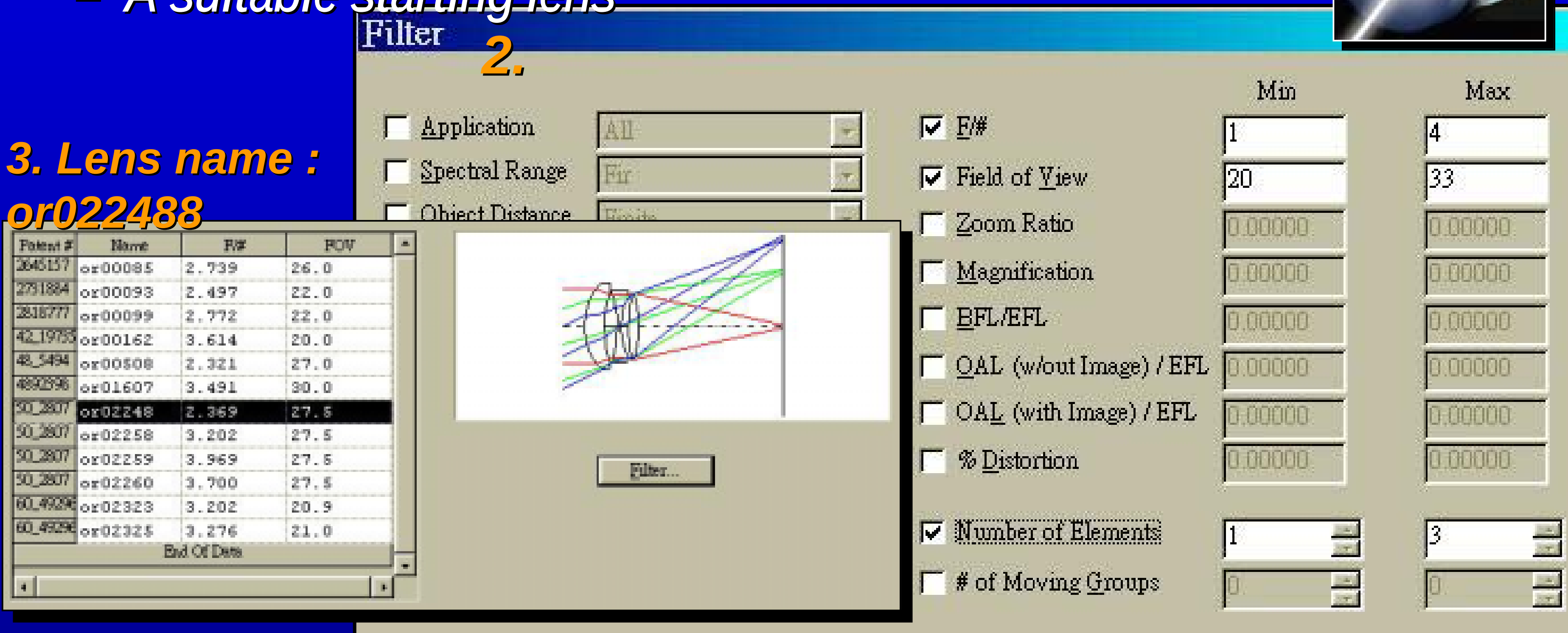
Selecting a suitable starting point

- The Code V New Lens Wizard
  - Searching existing designs- Patent Database
  - Filter
  - A suitable starting lens

1.

2.



3. Lens name : or022488

Patent #	Name	F/#	FOV
2645157	or00085	2.739	26.0
2731884	or00093	2.497	22.0
2816777	or00099	2.772	22.0
42_19755	or00162	3.614	20.0
48_5494	or00508	2.321	27.0
4892396	or01607	3.491	30.0
50_2807	or02248	2.369	27.5
50_2807	or02258	3.202	27.5
50_2807	or02259	3.969	27.5
50_2807	or02260	3.700	27.5
60_49296	or02323	3.202	20.9
60_49296	or02325	3.276	21.0

End Of Data

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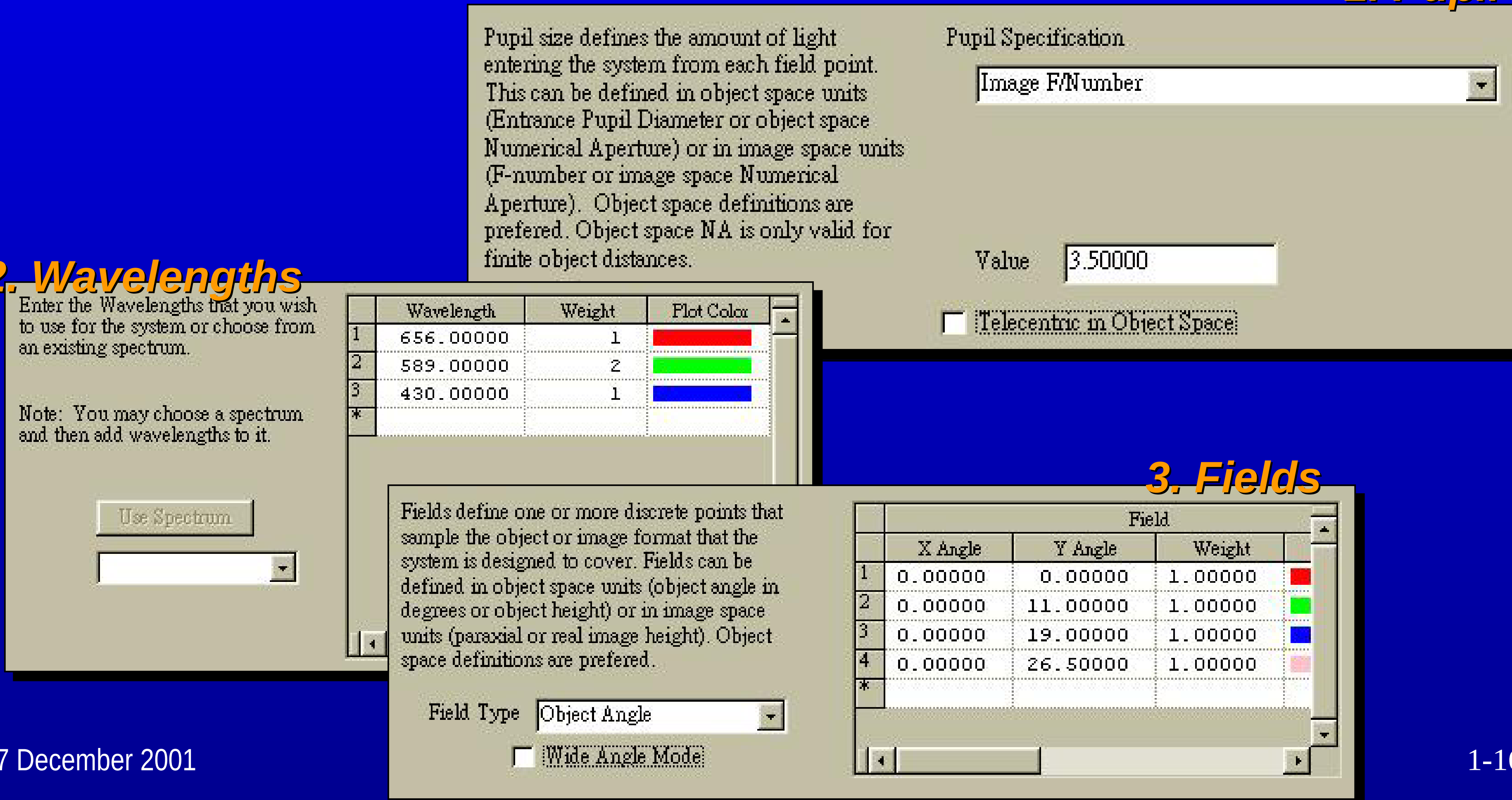
Selecting a suitable starting point

- *Defining system data*
  - *Pupil specification, Wavelengths, Fields…*

1. Pupil

2. Wavelengths

3. Fields



• Lens Data Manager Spreadsheet and Command Window

1. LDM Spreadsheet

Lens Data Manager

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi
Object		Sphere	Infinity	Infinity		Refract	
1		Sphere	0.35606	0.11000	786500.501	Refract	0.20624 O
2		Sphere	0.70116	0.07000		Refract	0.16825 O
3		Sphere	-0.65975	0.02000	717360.295	Refract	0.13294 O
Stop		Sphere	0.41684	0.03500		Refract	0.10884 O
5		Sphere	0.92080	0.06500	834810.429	Refract	0.14077 O
6		Sphere	-0.54079	0.77426 S		Refract	0.15209 O
Image		Sphere	Infinity	-0.00403		Refract	0.47506 O
		Sphere	End Of Data				

2. Command Window

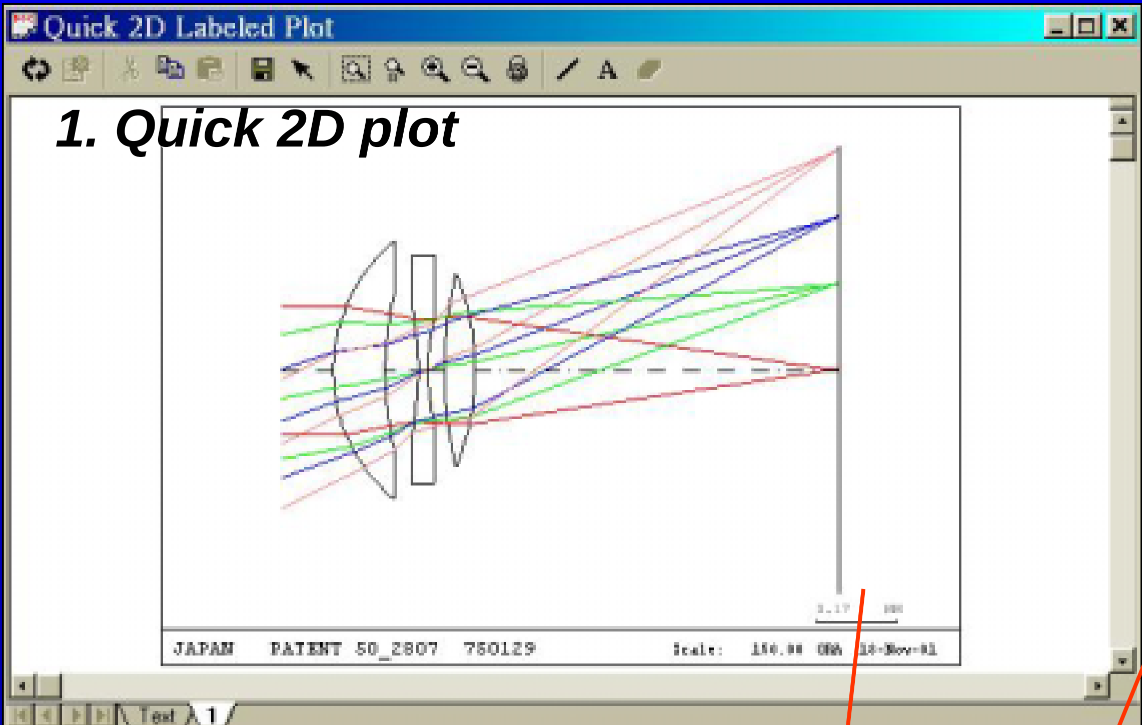
Command Window

Clear Text

```
LEN NEW
    Radius input/output mode
CODE V> IN CV_MACRO:cvnewlens.seq
CODE V>     RDM
CODE V>     LEN
CODE V>     TIT 'New lens from CVMACRO:cvnewlens.seq'
CODE V>     EPD 2
CODE V>     XOB 0
CODE V>     YOB 0
CODE V>     WL  587.5618

CODE V >
```

• Drawing Pictures and First order Data



2. First Order Data

List First Order Data

```
INFINITE CONJUGATES
   EFL          0.9528
   BFL          0.7743
   FFL         -0.8673
   FNO          3.5000
   IMG DIS      0.7702
   OAL          0.3000
   PARAXIAL IMAGE
    HT          0.4751
   ANG         26.5000
   ENTRANCE PUPIL
    DIA         0.2722
    THI         0.1949
   EXIT PUPIL
    DIA         0.2442
    THI        -0.0805
```

The lens system is too small

EFL, the result is not suitable for our specification

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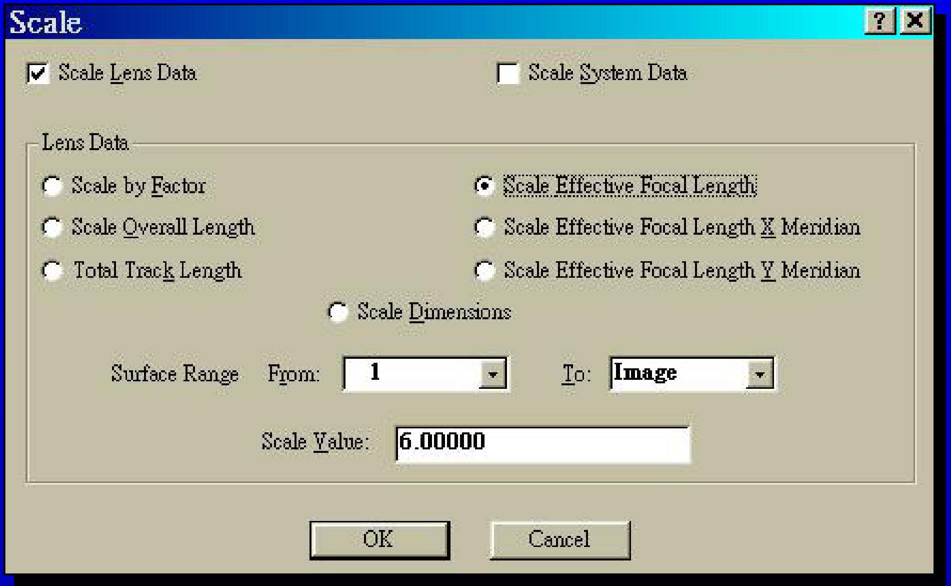
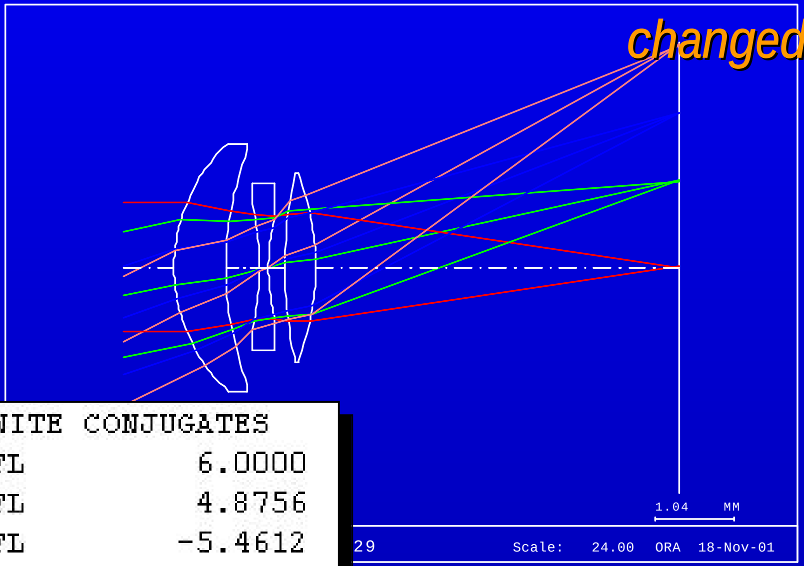
• Scale the Lens



• The lens data has been changed



Updated system layout

INFINITE CONJUGATES	
EFL	6.0000
BFL	4.8756
FFL	-5.4612
FNO	3.5000
IMG DIS	4.8502
OAL	1.8891
PARAXIAL IMAGE	
HT	2.9915
ANG	26.5000
ENTRANCE PUPIL	
DIA	1.7143
THI	1.2273
EXIT PUPIL	
DIA	1.5378
THI	-0.5067

The EFL value is now 6mm as desired.
The paraxial image height is 2.99 mm

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Analyze the Starting Point

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Analyze the Starting Point

- Basic and Useful Analysis
  - Ray aberration curves and Spot diagrams
- Compare with Lens Specifications
  - Distortion (Field Curve or Distortion Grid)
  - Sharpness (Diffraction MTF)
  - Vignetting

Focal length	Fixed, 6.0mm
Geometric Distortion	< 4%
Sharpness	MTF through focus range (central area is inner 3 mm of CCD)
	Low freq. 17 lp/mm: >90% (central), >85% (outer)
	High freq. 51 lp/mm: >30% (central), >25% (outer)
Vignetting	Corner relative illumination >60%
Transmission	Lens alone, >80% 400-700 nm

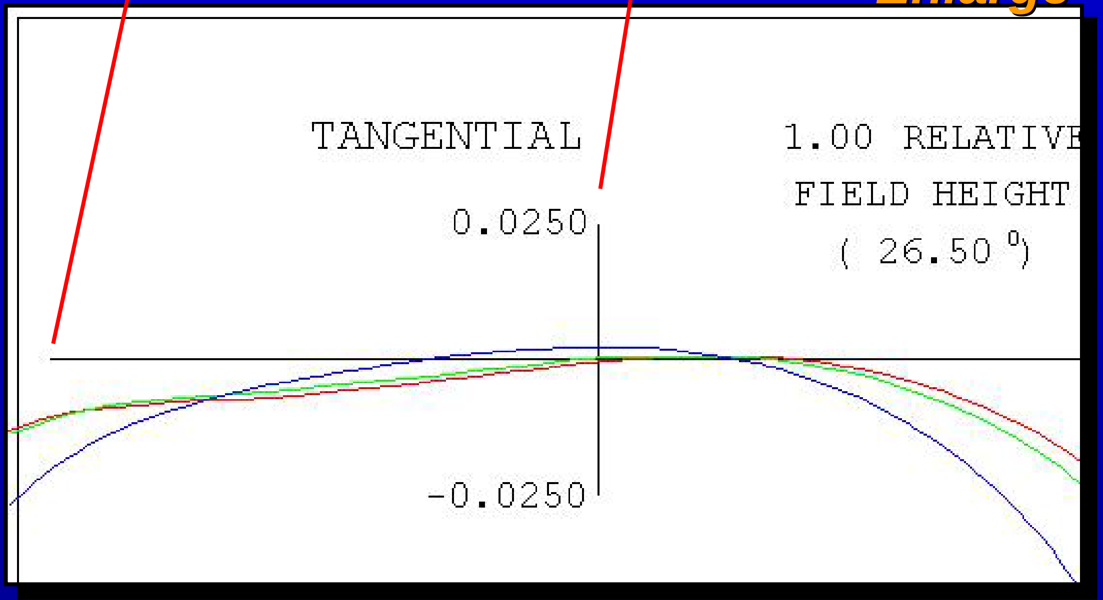
Ray Aberration and Spot Diagram

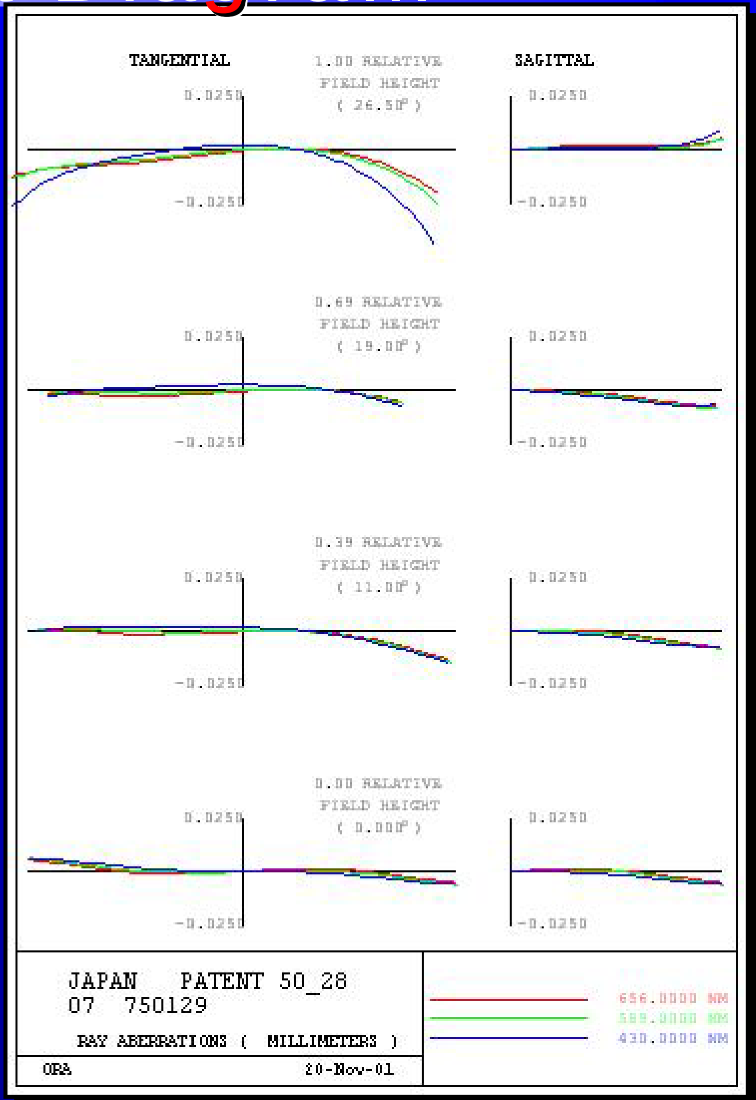
- ***Ray Aberration Curves***
  - *Analysis > Diagnostics > Ray Aberration Curve*

Aberration scale

Purple

Enlarge





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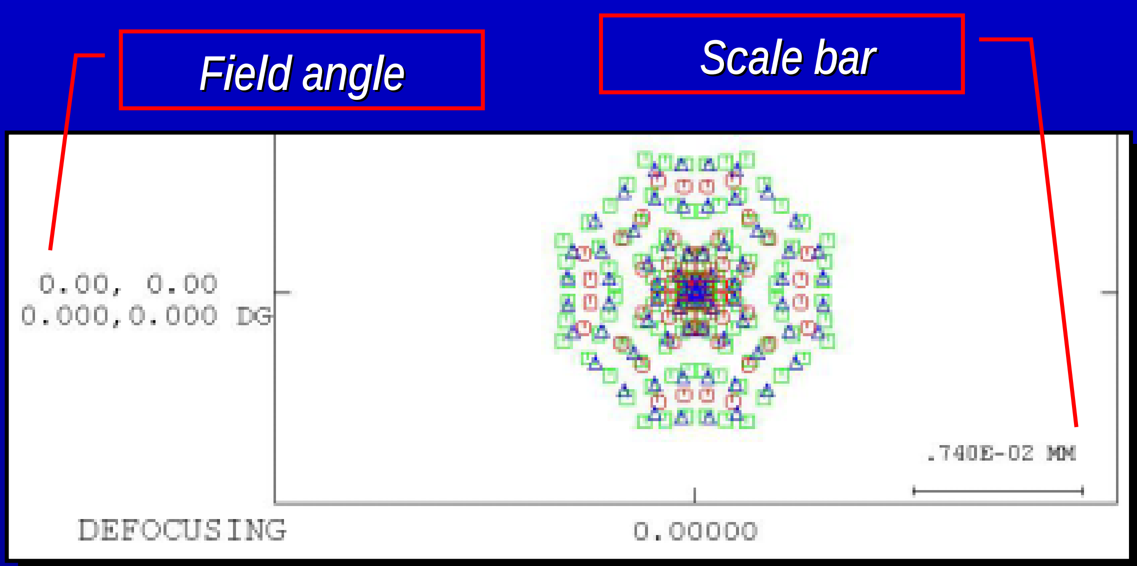
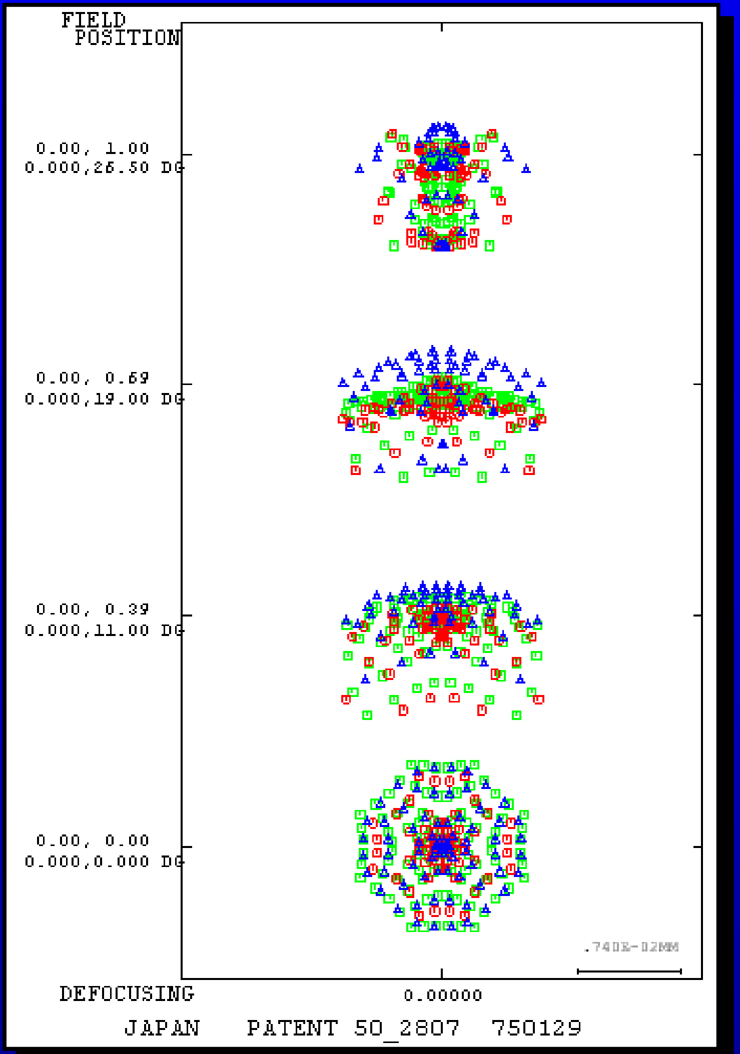
- ***Spot Diagram***
- *Analysis > Geometrical > Spot Diagram*
  - *Scale by Pixel Size 7.4 um*





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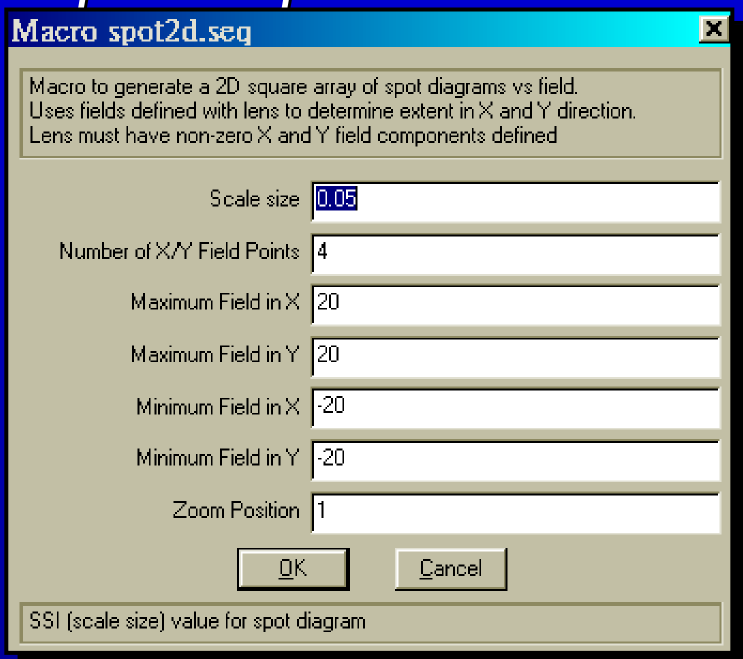
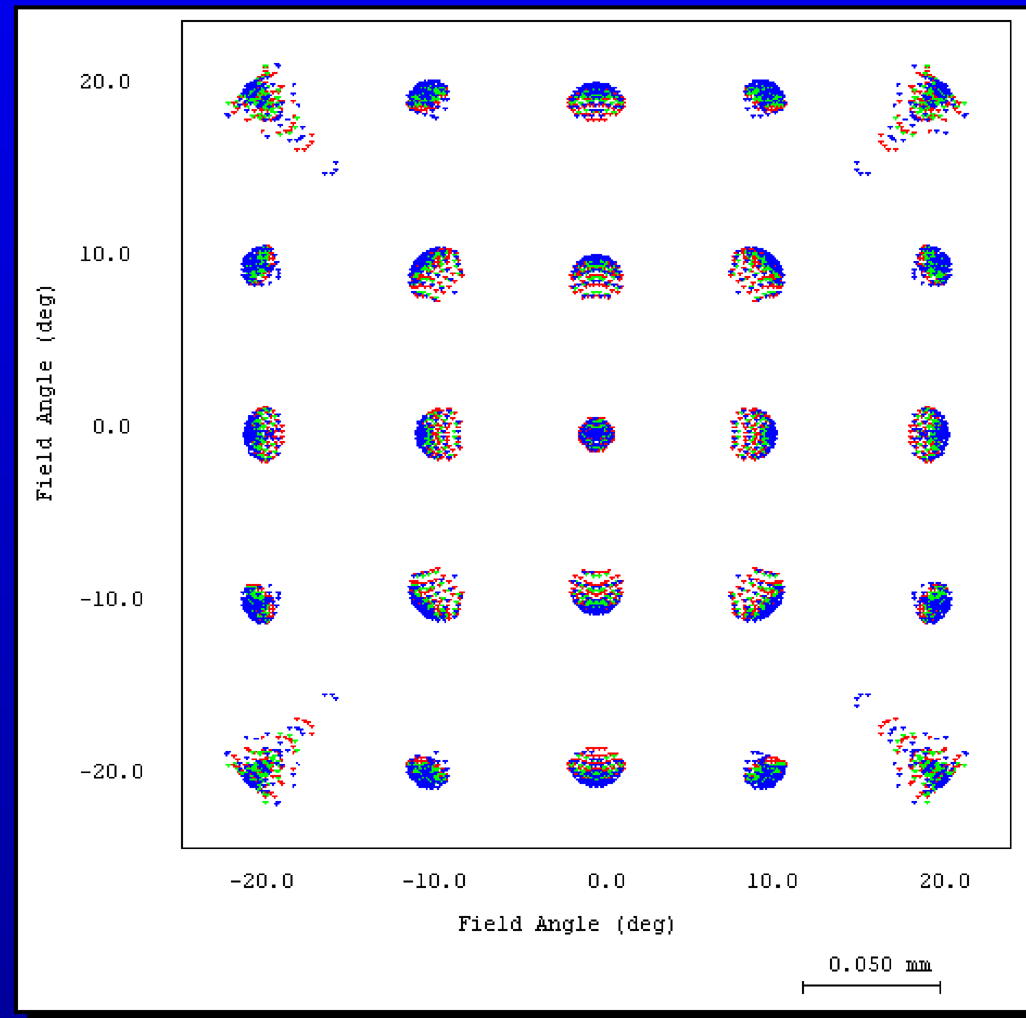
• Useful Spot Macro

- *Tool > Macro > Sample / Geometrical Analysis / sopt2d.seq*





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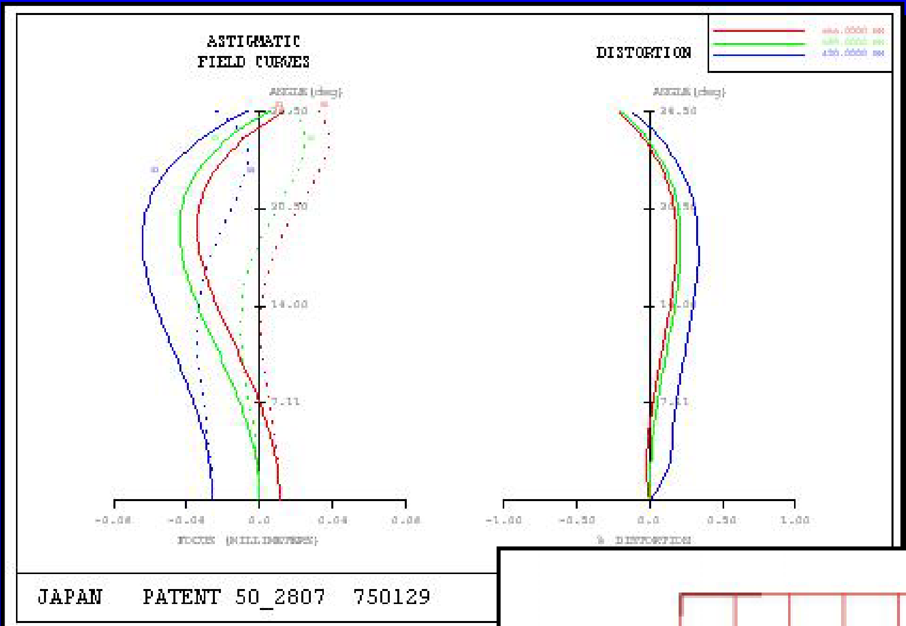
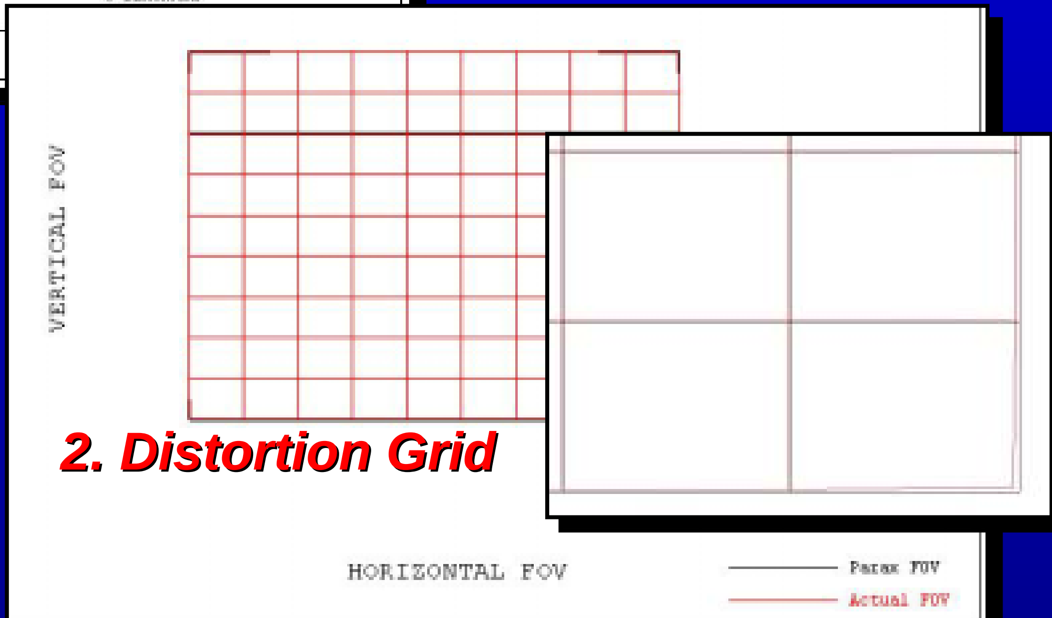
Distortion

- Analysis > Diagnostics > Field Curve
- Analysis > Diagnostics > Distortion Grid



1. Field Curve



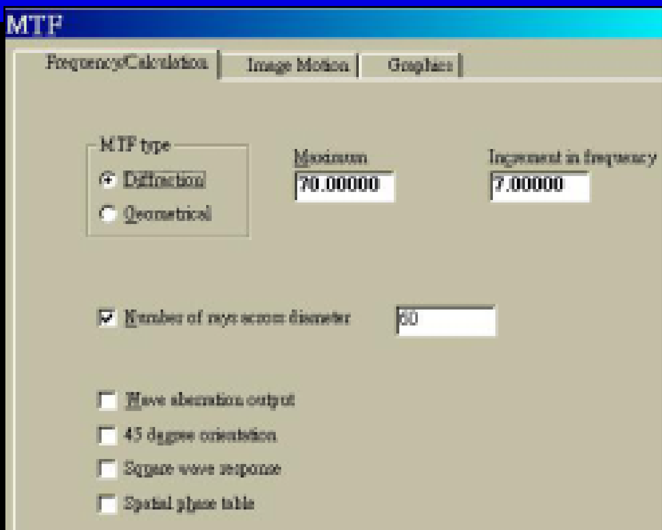
2. Distortion Grid

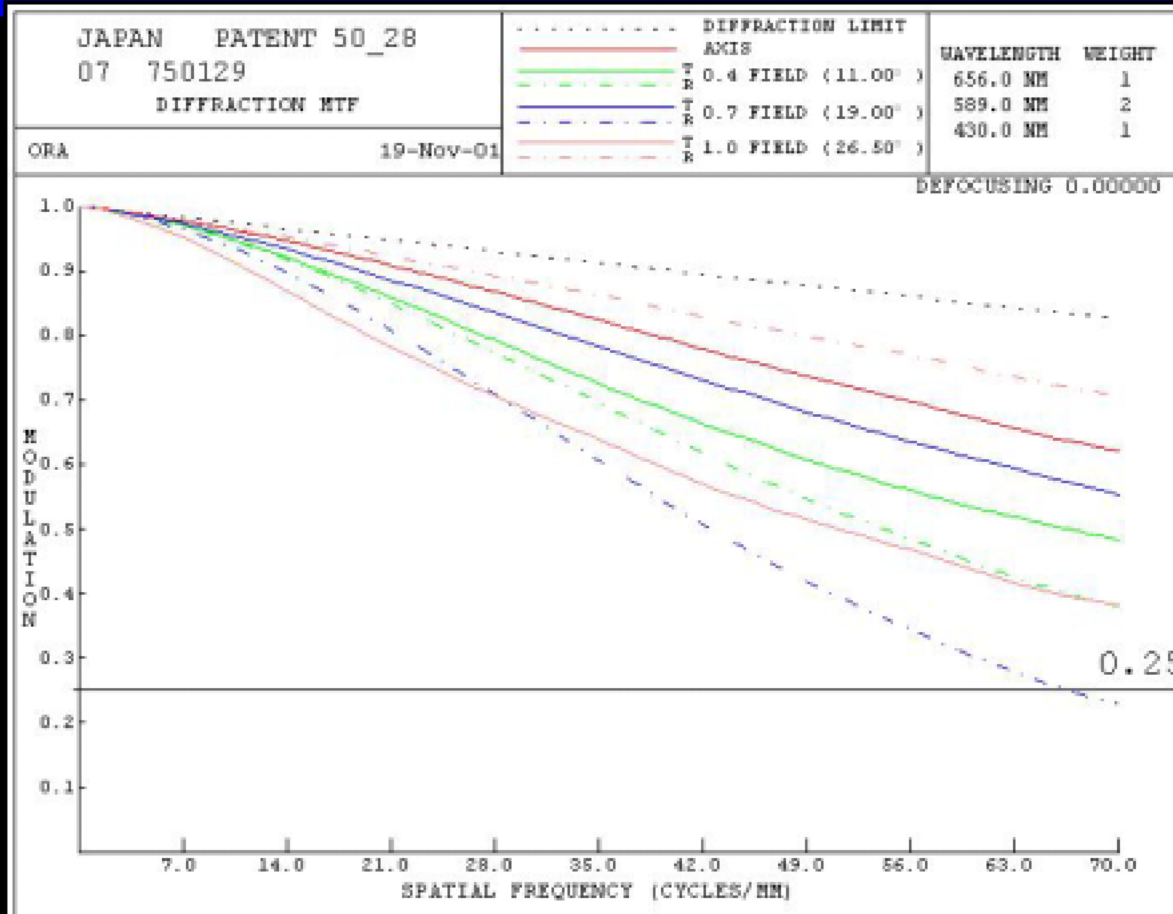
MTF Output

- *Analysis > Diffraction > MTF*

Sharpness *MTF through focus range (central area is inner 3 mm of CCD)*

Low freq. 17 lp/mm	*> 90% (central)*	*> 85% (outer)*
High freq. 51 lp/mm	*> 30% (central)*	*> 25% (outer)*





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Vignetting	Corner relative illumination > 60%	Transmission	Lens alone, > 80% 400-700 nm

Vignetting / Illumination and Transmission

1. Get from Text tab of MTF output
2. Analysis > system > Transmission Analysis

1.

Digital VGA Camera

```
FIELD (X,Y)=( 0.00, 1.00)MAX, (  0.00, 26.50)DEG
RELATIVE ILLUMINATION =   66.4 PER CENT
ILLUMINATION (UNIT BRIGHTNESS) = 0.043192
DISTORTION =  -0.20 PER CENT
```

	DIFFRACTION LIMIT			FOCUS POSITION	
	Formula	Actual		0.00000	
L/MM	f/3.500	RAD	TAN	RAD	TAN
0	.999	.999	.999	.999	.999
7	.982	.981	.977	.978	.950
14	.965	.962	.953	.952	.868
21	.947	.942	.929	.922	.781
28	.929	.923	.906	.892	.705
35	.912	.904	.881	.862	.637
42	.894	.885	.858	.829	.569
49	.877	.866	.835	.799	.514
56	.859	.846	.812	.769	.467
63	.842	.828	.789	.735	.416
70	.824	.809	.767	.707	.381

Relative Illumination

2.

PRODUCT	REF	0.9361	0.9648	0.8961	0.9404
	ABS	1.0000	1.0000	1.0000	1.0000
Ave Transmittance:		0.9361	0.9648	0.8961	0.9404
ILLUMINATION:		0.04042	0.04173	0.03911	0.04075
RELATIVE ILLUM:		64.0	64.9	69.7	65.7
PROJECTED SOLID ANGLE (IMAGE SPACE):		0.04318	0.04326	0.04365	0.04334
USED AREA OF ENTRANCE PUPIL:		2.29240	2.29333	2.29596	2.29376

Illumination and Transmission for each wavelength

* Transmission data missing for this material; 100% transmission assumed.

User-specified transmission data can be provided as part of the lens data.

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Picking on Glass

- Tool > Macro > glassfit.seq
  - Sample Macro / Material Information

Macro glassfit.seq

Macro to help the user convert fictitious (variable) glasses into real glasses. Several fitting methods are available. The macro prompts for all required inputs (Q to quit).

Multiplier for Delta-V: 1

Eliminate disc. glasses?: Yes

OK | Cancel

Relative importance of Delta-V to Delta-N

- **Result of glassfit.seq**

```
Availability Codes:

Catalog     Code     Definition
-------     ----     ----------

All           3      Discontinued
              4      Discontinued with recommended replacement glass
              5      Preliminary


Schott        0      Preferred glass
              1      Standard Glass
              2      Inquiry Glass
```

Surf	Catalog	Glass	Delta Nd	Delta Vd	Avail	Price	DPF	Bubl	Stain
1	SCHOTT	LAFN28	0.01336	0.5317	1	315.00	-75	0	1
3	SCHOTT	SF1	0.00000	-0.0129	0	36.50	0	1	1
5	SCHOTT	NLASF41	-0.00020	-0.2291	2	0.00	-79	1	0

Optimization: Making Things Better

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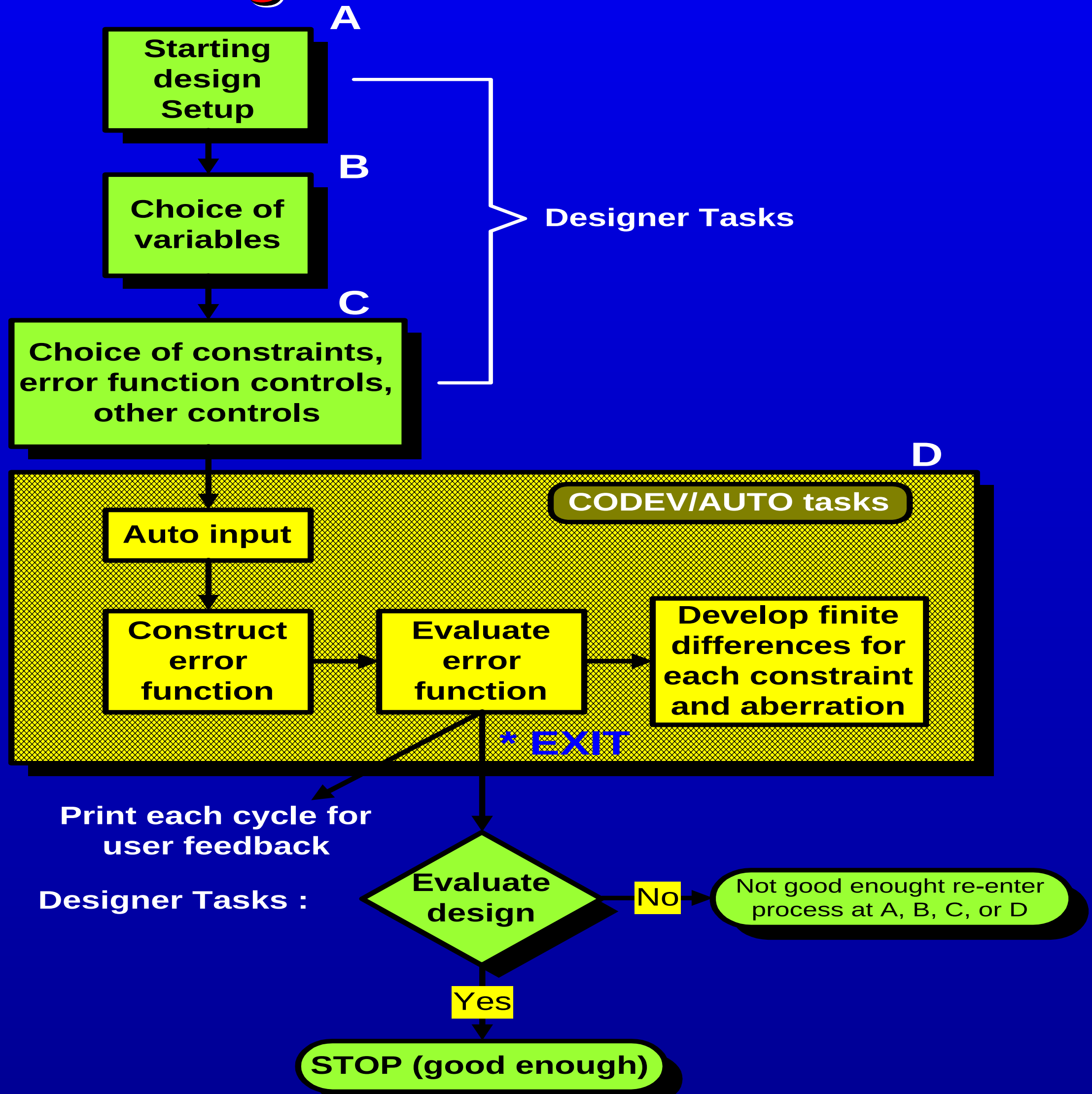
Automatic Design Process



The Game Plan

- *Define as variable: all radii of curvatures, thickness values, and fictitious glasses*
- *Automatic Design Setting*
  - *Make sure all glass elements are thick enough and glass index doesn't get too high*
  - *Constrain the effective focal length (EFL) to the current 6 mm*
  - *Use the default spot size (transverse ray aberration) error function,but trace mire rays in the grid*
- *optimizations*
  - *Run AUTO*
  - *Understanding the output and reevaluations*
  - *Modify AUTO setting to refine the solution*

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Defining Variable

- *Variables are defined in the LDM*
  - *To vary the constructs what you want, place the cursor on the it in the LDM window, right-click, and choose " Vary" from the shortcut menu.*

The red, small letter "V " means variable

Lens Data Manager

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	O
1		Sphere	2.24216 V	0.69268 V	786500.501 V	Refract	1.29873 O
2		Sphere	4.41530 V	0.44080 V		Refract	1.05951 O
3		Sphere	-4.15453 V	0.12594 V	717360.295 V	Refract	0.83714 O
Stop		Sphere	2.62490 V	0.22040 V		Refract	0.68537 O
5		Sphere	5.79840 V	0.40931 V	834810.429 V	Refract	0.88647 O
6		Sphere	-3.40543 V	4.87562 S		Refract	0.95772 O
Image		Sphere	Infinity	-0.02539		Refract	2.99149 O

End Of Data

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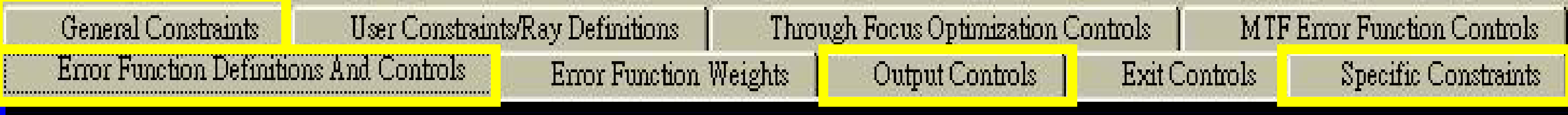

Automatic Design Setting

- *The first boundary condition category is General Constraint*
  - *General Thickness Constraint*
  - *Glass Map Constraint*
- *The second boundary condition category is Specific Constraint*
  - *Edit Constraint : Optical Definition / First Order or Third Order Aberration ……*
  - *Defining Constraint Mode and Constraint Target*
- *Error Function Definitions and Controls*
  - *Error Function Types*
- *Output Controls*

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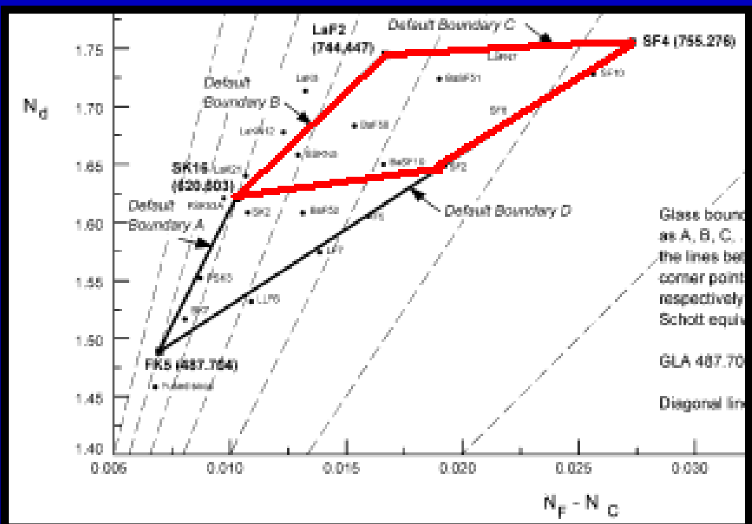
General Constraints | User Constraints/Ray Definitions | Through Focus Optimization Controls | MTF Error Function Controls
Error Function Definitions And Controls | Error Function Weights | Output Controls | Exit Controls | Specific Constraints

General Constraint

- *Min. center thickness*
  - *0.9 mm*
- *Min. edge thickness*
  - *0.8 mm*
- *Defining new corner point for the glass map*



The following constraints can be overridden on specific surfaces by use of specific constraints:

Maximum center thickness: 1.30000
Minimum edge thickness: 0.80000
Minimum air edge: 0.00250
Minimum center thickness: 0.90000
Minimum axial air: 0.10000

Maximum angle of incidence

	Start Surface	End Surface	Max. Angle
*			

Glass map boundary glasses/points (enter 3-5 values, default Schott, NFK5, NSK16, NLAF2, .

	Start Surface	End Surface	Map 1	Map 2	Map 3	Map
1	Object	Image	NFK5	NSK16	SF2	
*						

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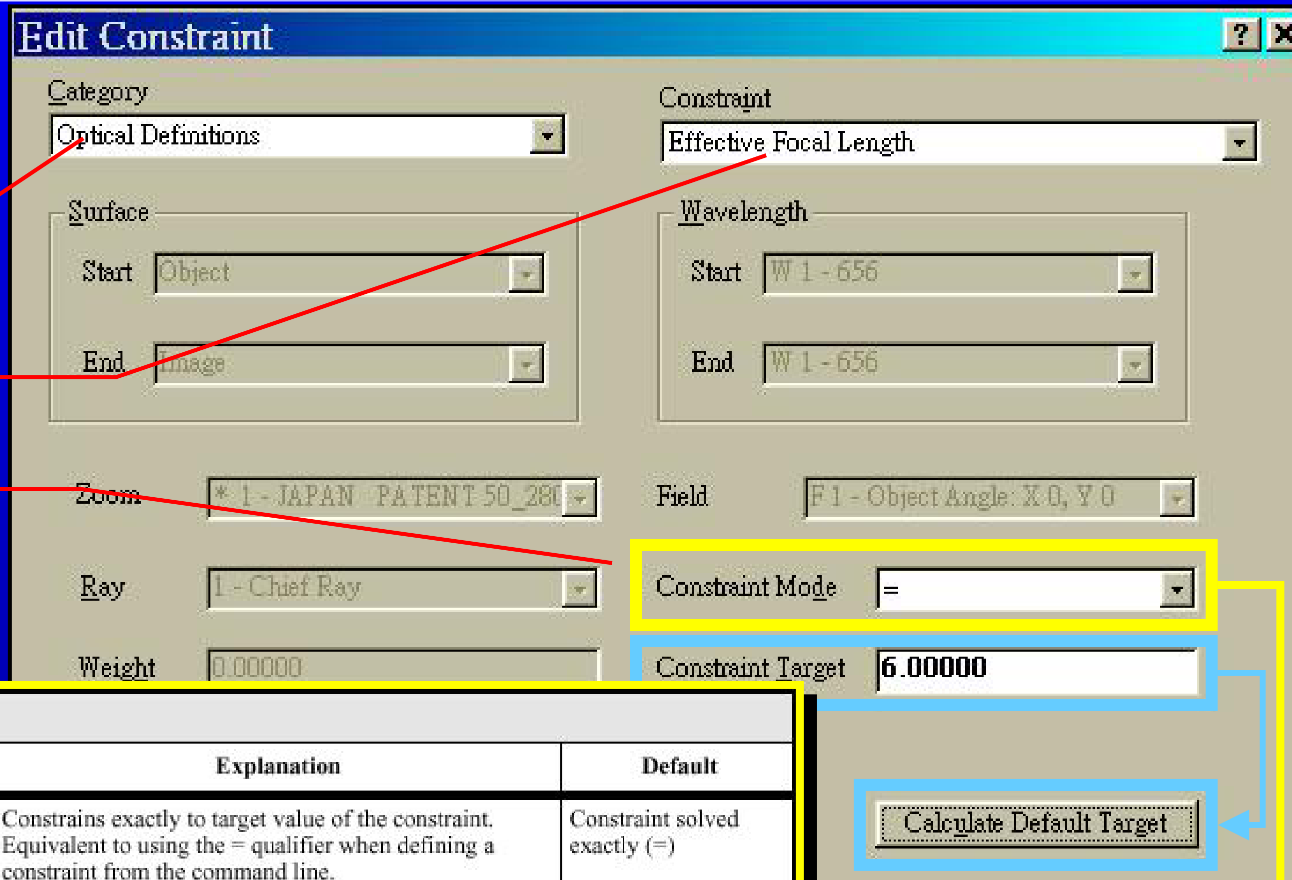
Specific Constraint

- Constraint
  - EFL

Constraint category

Constraints

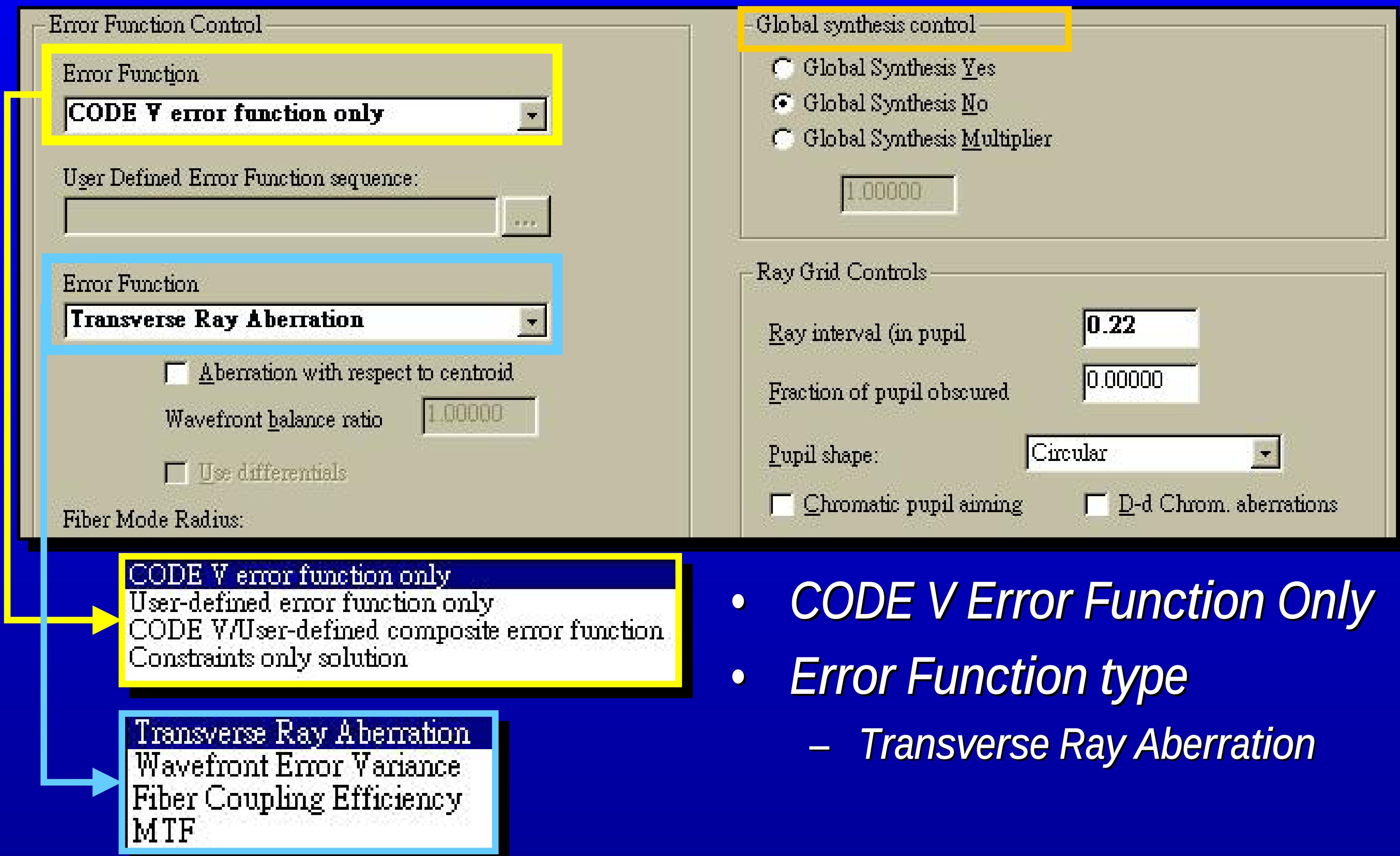
Constraints mode



Command Syntax

Screen Control	Explanation	Default
Constraint Mode: =	Constrains exactly to target value of the constraint. Equivalent to using the = qualifier when defining a constraint from the command line.	Constraint solved exactly (=)
Constraint Mode: >	Defines target value of the constraint as a minimum value, or lower boundary. Equivalent to using the > qualifier when defining a constraint from the command line.	Constraint solved exactly (=)
Constraint Mode: <	Defines target value of the constraint as a maximum value, or upper boundary. Equivalent to using the < qualifier when defining a constraint from the command line.	Constraint solved exactly (=)

Error Function Definition and Controls



- *CODE V Error Function Only*
- *Error Function type*
  - *Transverse Ray Aberration*

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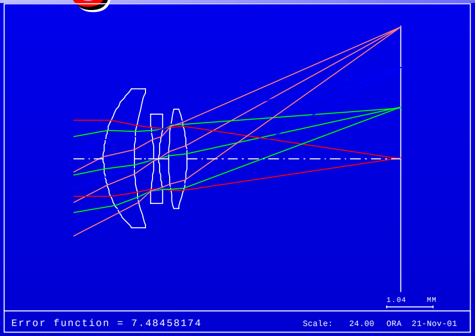
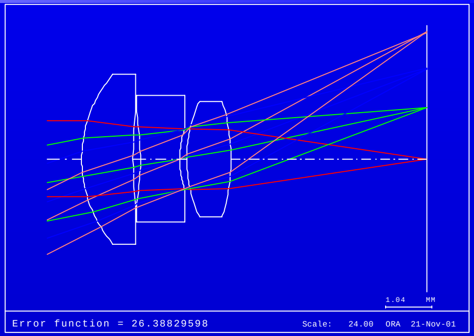
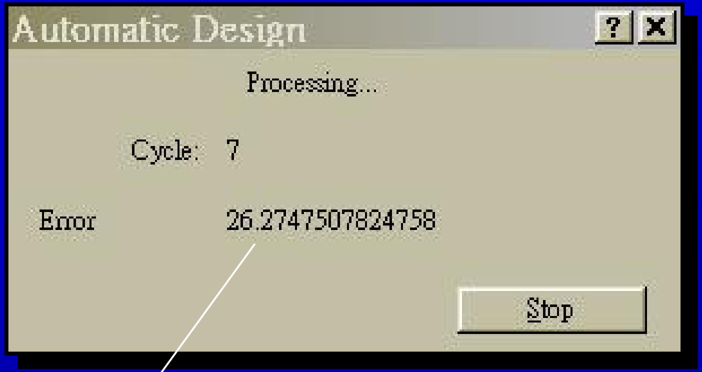
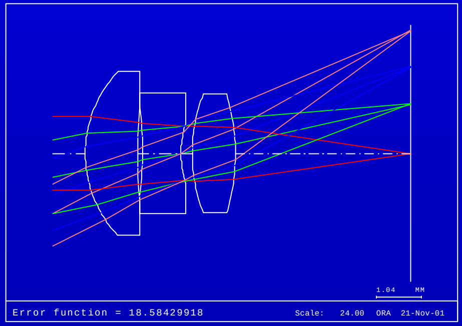
Run Automatic Design

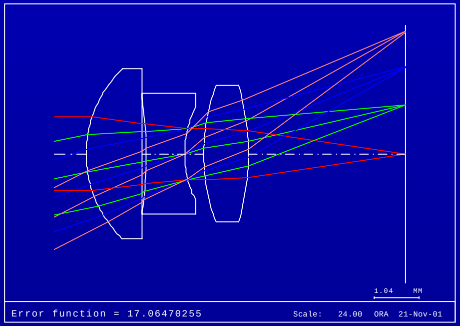


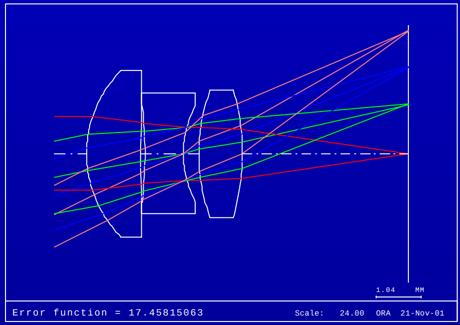






Error function valve





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Understanding AUTO Output

```
Active Constraints -  9:     target        value        diff        cost
EFL Z1                =   6.00000E+00   6.15943E+00   1.594E-01   2.103E-05
GL A S1                                                          1.759E-06
GL B S1                                                          2.903E-05
GL C S3                                                          4.477E-05
GL B S5                                                          9.355E-05
Mn ET S1                                                        -1.597E-05
Mn ET S2                                                        -4.367E-05
Mn CT S3                                                        -1.205E-04
Mn ET S5                                                        -4.150E-05

Display-only Constraints:   value                                  value
DIY F4 Z1             = -8.32743E-03

CYCLE NUMBER 1:

ERR. F.  =       49.50252745        (change =      42.01794572)

 X       3.42910119      8.40039817     21.00789155    25.01625504
 Y       3.42910119      5.62868597     11.10440115   119.99427554
```

Active constraints

Error function contributions

Error function contributions

Error function change

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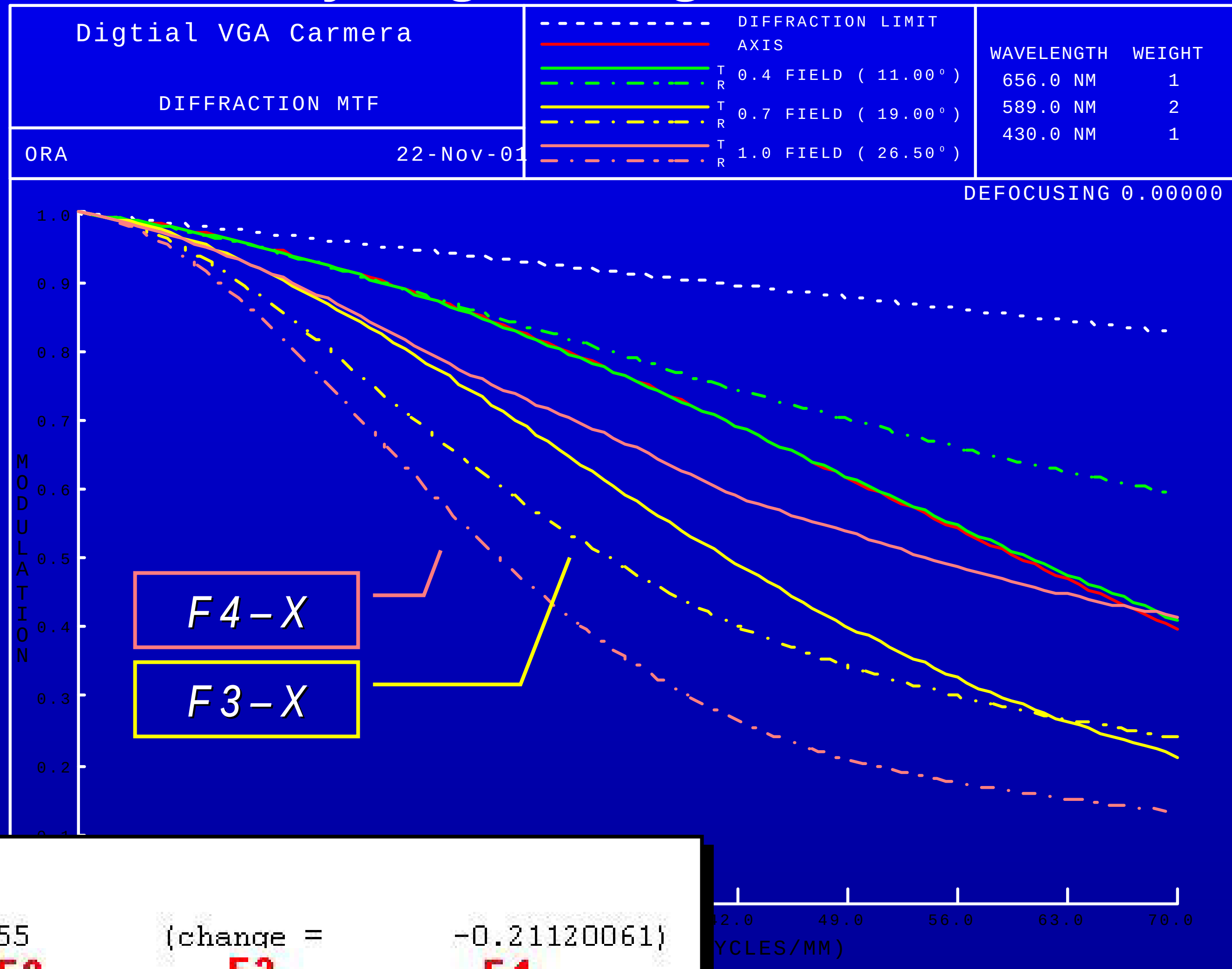
General Constraints | User Constraints/Ray Definitions | Through Focus Optimization Controls | MTF Error Function Controls

Error Function Definitions And Controls | **Error Function Weights** | Output Controls | Exit Controls | Specific Constraints

Analyzing and Modifying Weights



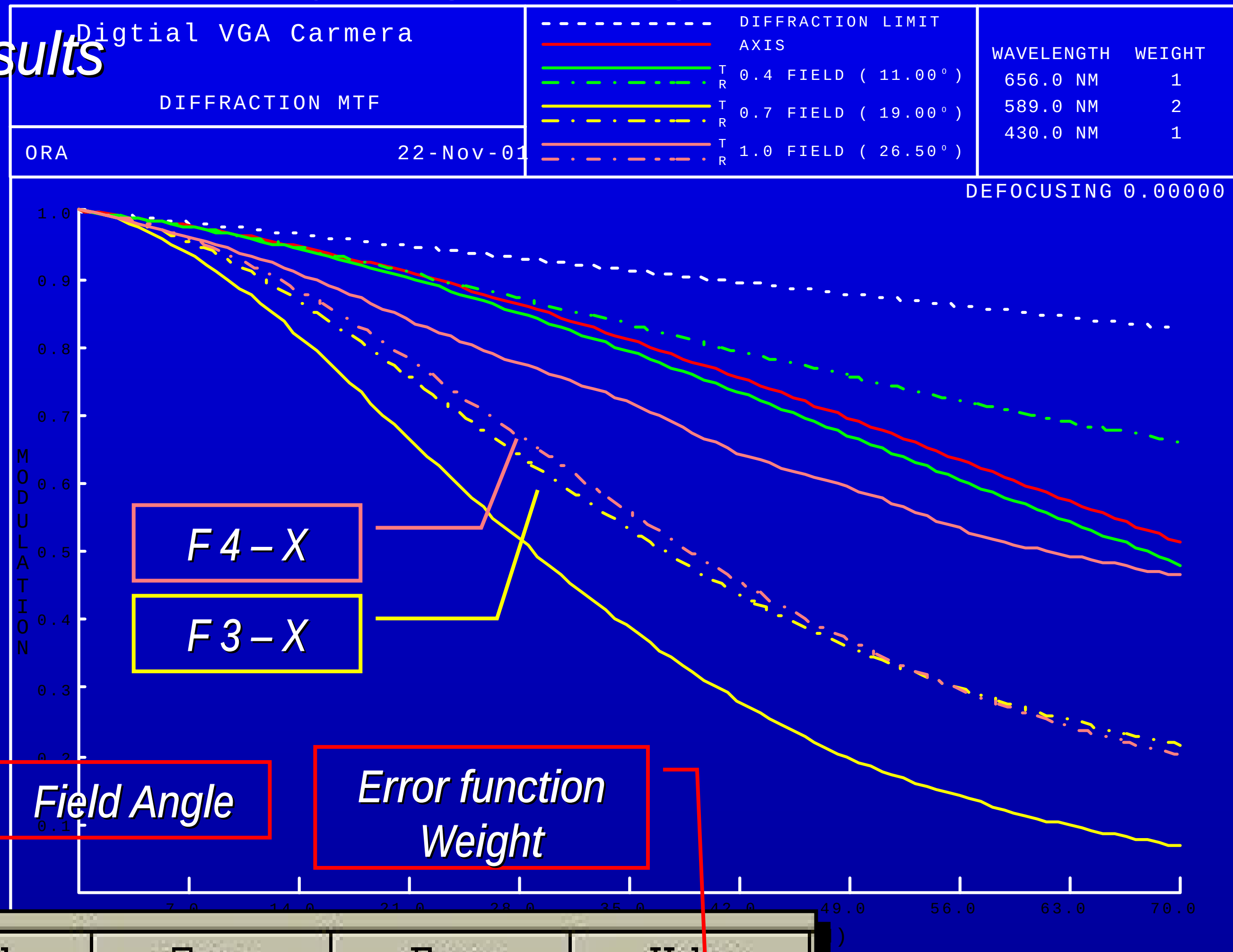
CYCLE NUMBER 8:

ERR. F. = 17.06470255 (change = -0.21120061)

	F1	F2	F3	F4
X	5.37660053	3.16298930	11.98027165	17.27086010
Y	5.37660053	5.85679282	12.06500095	7.16969432

Analyzing and Modifying Weights

- Optimized MTF Results



Aberration Direction

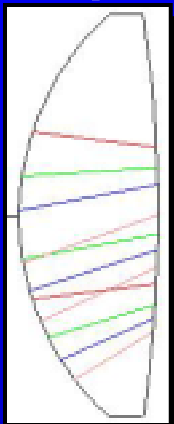
Field Angle

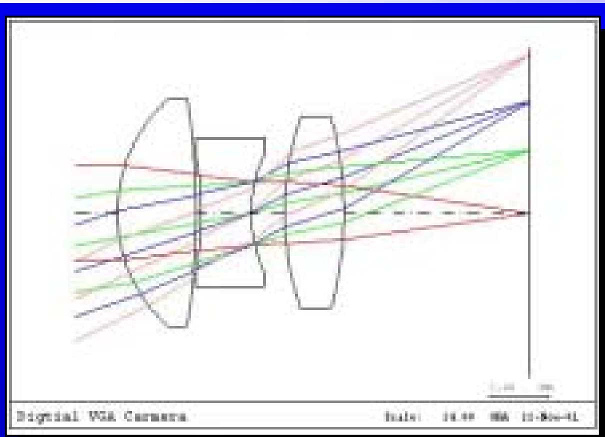
Error function Weight

X-Aberration weights only

	Field	Zoom	Focus	Value
1	F 3 - Ob	All Zoom	1	1.2
2	F 4 - Ob	All Zoom	1	Default

Optimization and Re-evaluations (1)





X- and Y-Aberration weights

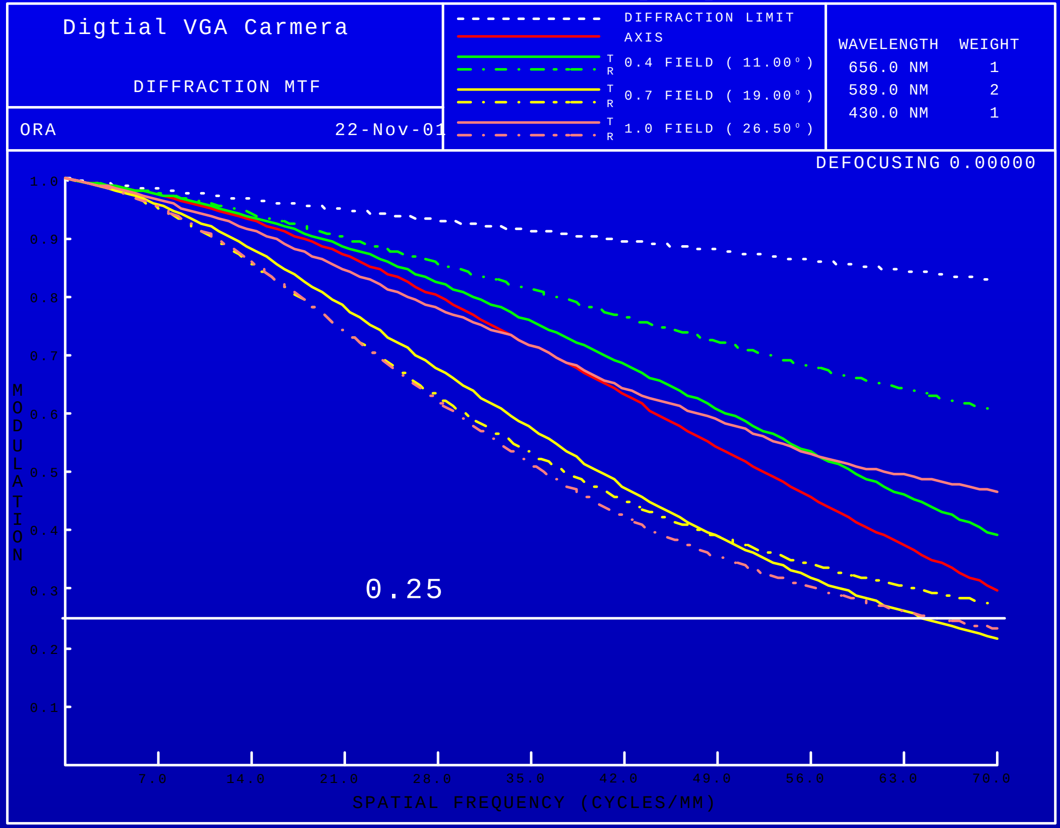
	Field	Zoom	Focus	Value
1	F 1 - Ob	All Zoom	1	0.8
2	F 2 - Ob	All Zoom	1	0.8
*				

X-Aberration weights only

	Field	Zoom	Focus	Value
1	F 3 - Ob	All Zoom	1	1.2
2	F 4 - Ob	All Zoom	1	1.3
*				

Y-Aberration weights only

	Field	Zoom	Focus	Value
1	F 3 - Ob	All Zoom	1	1.5
*				



- *The results are accepted for infinite objection distance*

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Error Function Definitions And Controls | Error Function Weights | Output Controls | Exit Controls | Specific Constraints

Optimization and Re-evaluations (2)

- *Optimization for objection distance =750 mm*
  - *Consider the defocus effect (Through focus)*
  - *The error functions are weighting by different focus*

Defocus defining

Through focus values

	Defocus Values	Defocus Weight	Focus Num	
1	0	1.0	1	* 1 –
2	-0.048	1.0	2	* 1 –
*				

Focus assigning

X- and Y-Aberration weights

	Field	Z
1	F 1 – Ob	All Z
*		

X-Aberration weights only

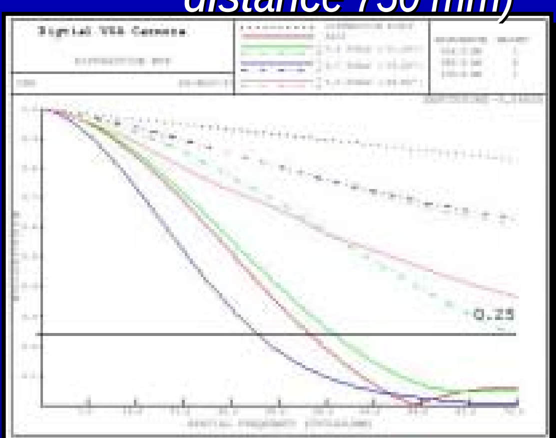
	Field	Zoom	Focus	Value
1	F 3 – Ob	All Zoom	1	2.9
2	F 4 – Ob	All Zoom	1	2.9
3	F 3 – Ob	All Zoom	2	0.1
4	F 4 – Ob	All Zoom	2	0.1
5	F 2 – Ob	All Zoom	2	0.1

0.1

Y-Aberration weights only

	Field	Zoom	Focus	Value
1	F 3 – Ob	All Zoom	2	4
2	F 2 – Ob	All Zoom	1	0.1
3	F 3 – Ob	All Zoom	1	0.1
4	F 4 – Ob	All Zoom	1	1.3
*				

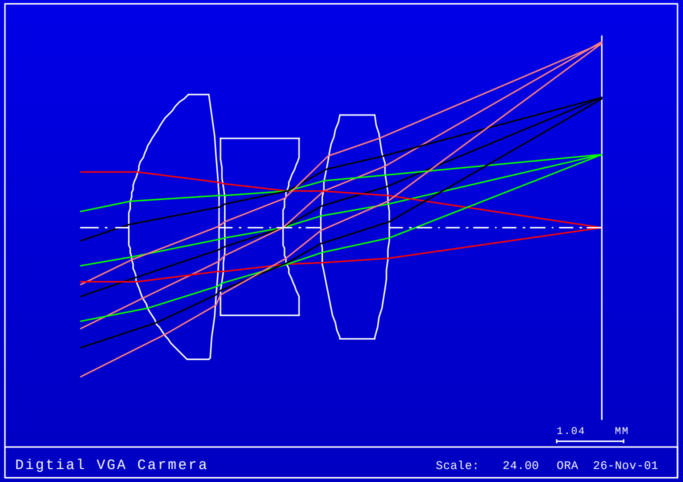
•*MTF (object distance 750 mm)*



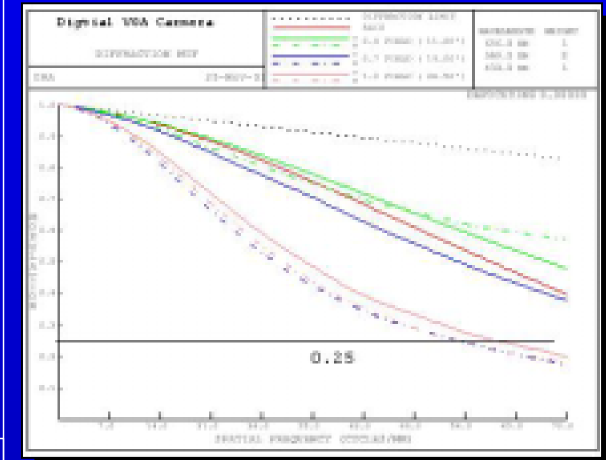
Optical System Design

Final Evaluations

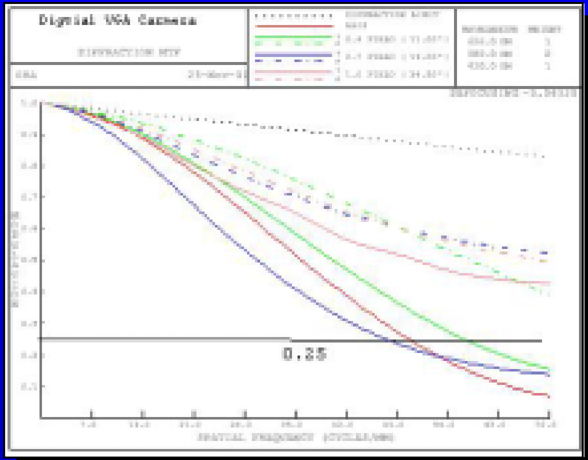
Sharpness	MTF through focus range (central area is inner 3 mm of CCD)	
Low freq. 17 lp/mm	> 90% (central)	> 85% (outer)
High freq. 51 lp/mm	> 30% (central)	> 25% (outer)



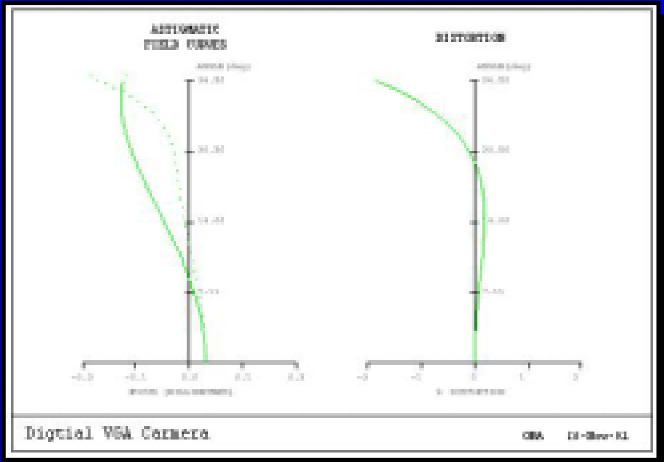
• MTF at defocus 0 mm



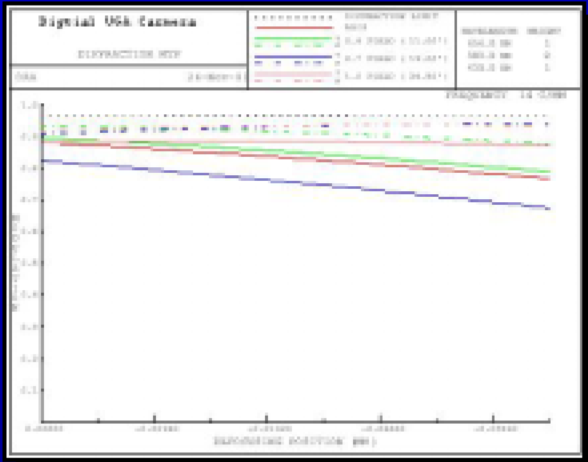
• MTF at defocus –0.048 mm

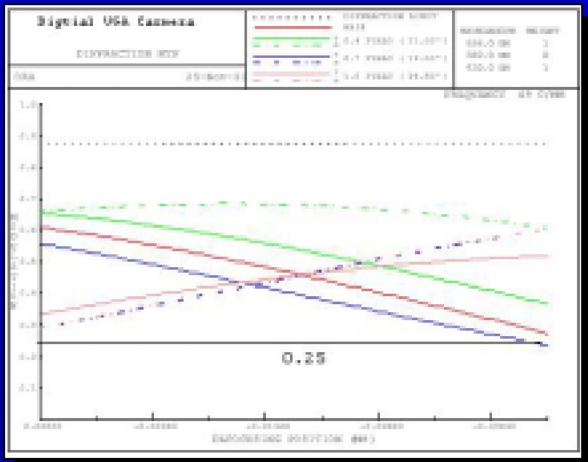


• Field curve and Distortion



• Through focus MTF at defocus 17 lp/mm and 51 lp/mm





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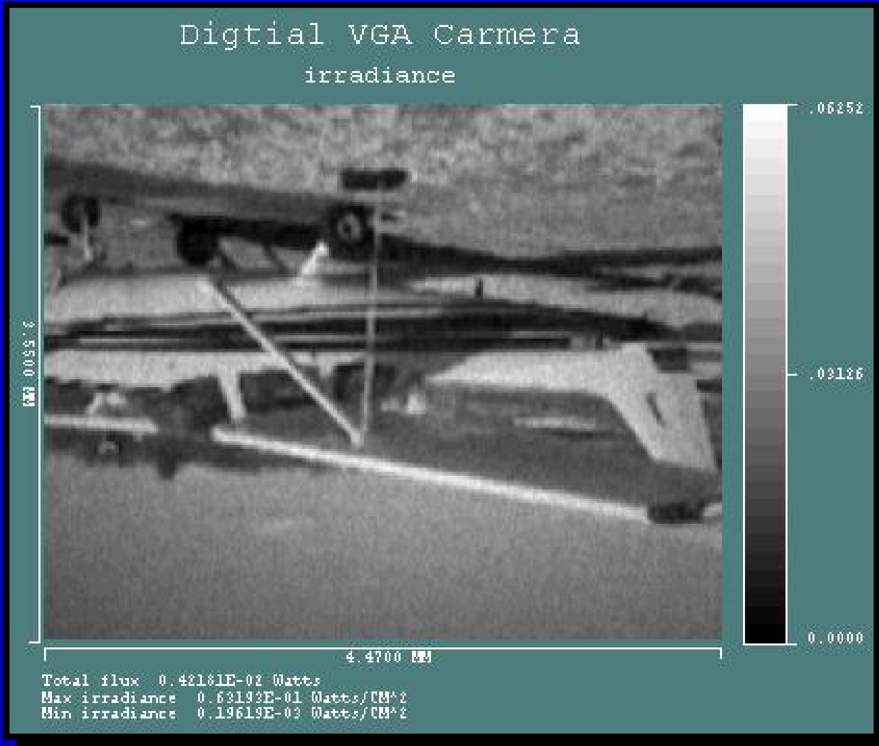
Final Evaluations – illumination

- *Analysis > Illumination*
  - *Using Bitmap images as illumination source*
  - *The imaging process is base on Raytrace method*



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