Section 2
Digital Camera Design Study

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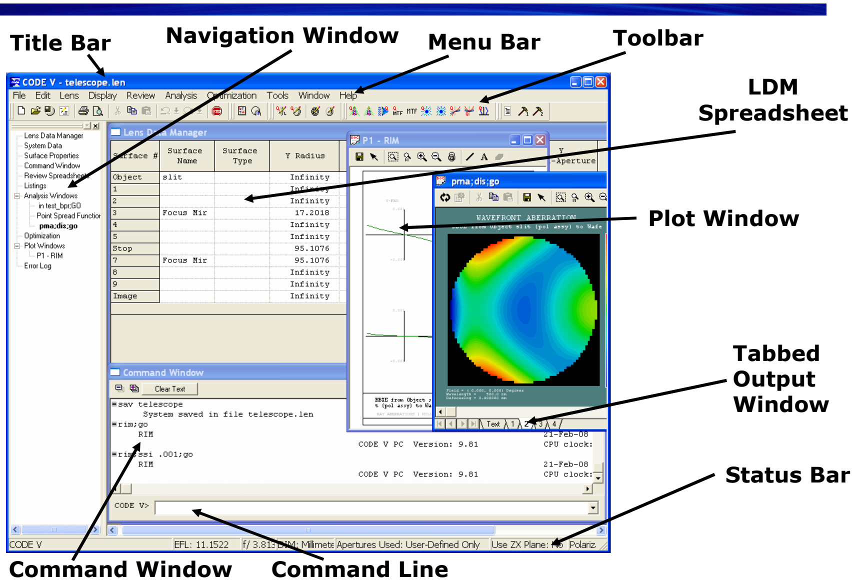
Interface Elements



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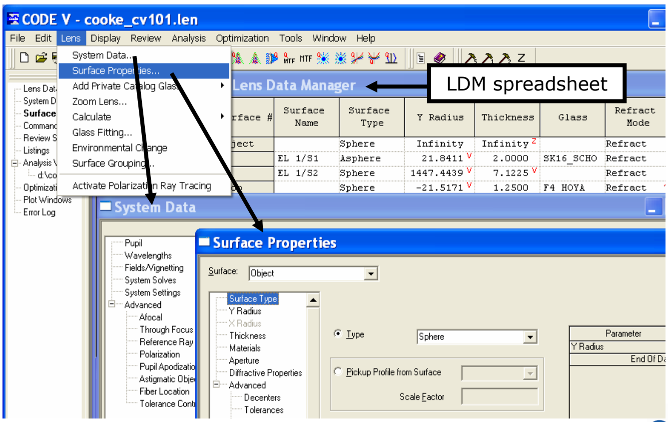
Lens Data specified by Lens Data Manager (LDM)

- 3 main windows for entering data
  - Lens Data Manager spreadsheet
  - System Data
  - Surface Properties



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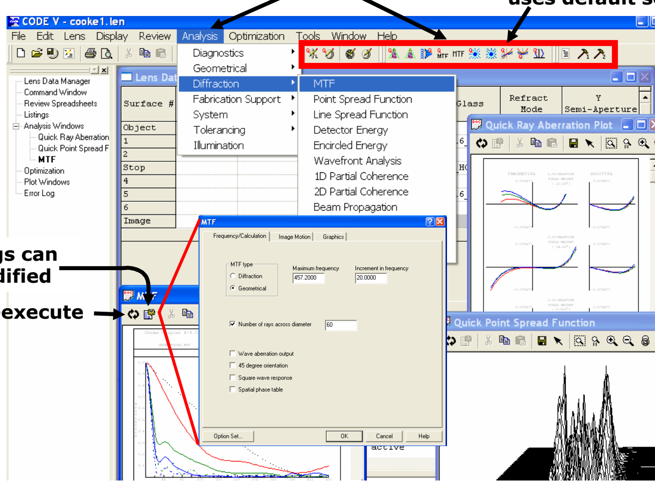
Analysis functions referred to as options (with input settings)

Menu or toolbar access

Q on toolbar button indicates "quick" option uses default settings



Settings can be modified

Re-execute

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Example: Digital Camera Lens

- **Small number of elements (1-3) made from common glasses or plastics**
- **Image sensor (baseline is Agilent FDCS-2020)**

a. Type	CMOS
b. Resolution	640 x 480 effective pixels
c. Pixel size	7.4 x 7.4 microns
d. Sensitive area	3.55 x 4.74 mm (full diagonal 6 mm)

- **Objective Lens**

e. Focus	Fixed, depth of field 750 mm (2.5 ft.) to infinity
f. Focal length	Fixed, 6.0 mm
g. Geometric Distortion	<4%
h. f/number	Fixed aperture, f/3.5
i. Sharpness	MTF through focus range (central is inner 3 mm of CCD)

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

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

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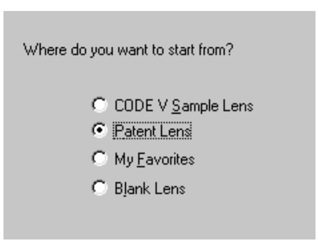
Run the New Lens Wizard

- Choose the **File > New** menu to launch the NLW
  - Click **Next>** to clear the Welcome Screen
  - Click the Patent Lens button, then click **Next>**



- Click the **Filter** button to open the patent filter dialog

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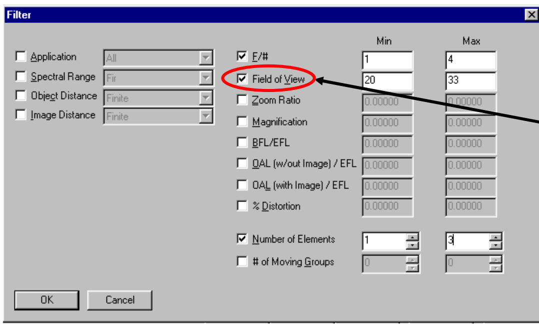
Filter Dialog

- Check the items of interest and enter Min and Max values for each, then click **OK**.
  - F/# goal is 3.5 (try 1 to 4), Field of View goal is 26.5° (try 20 to 33), try 1 to 3 for number of elements.



Note that this is actually the semi-field of view, which corresponds to object or image height

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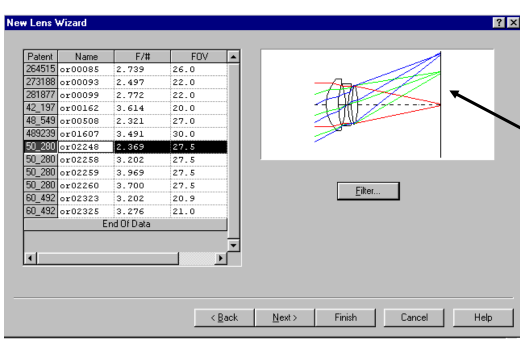
Filter Results

- The filter returns around 12 lenses
  - Wider field and faster f/number than needed is best
  - The triplet or02248 looks pretty good (f/2.4, 27.5°)
- Click the **Next>** button



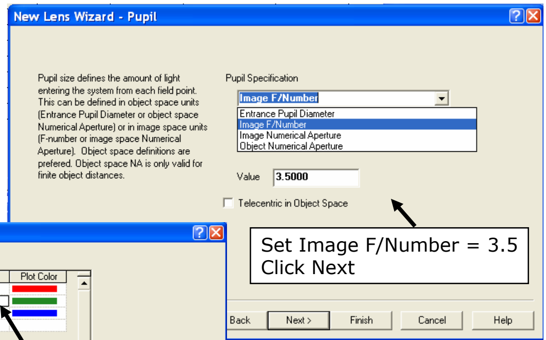
Patent	Name	F/#	FOV
264515	or00085	2.739	26.0
273188	or00093	2.497	22.0
281877	or00099	2.772	22.0
42_197	or00162	3.614	20.0
48_549	or00508	2.321	27.0
489239	or01607	3.491	30.0
50_280	or02248	2.369	27.5
50_280	or02258	3.202	27.5
50_280	or02259	3.969	27.5
50_280	or02260	3.700	27.5
60_492	or02323	3.202	20.9
60_492	or02325	3.276	21.0
End Of Data			

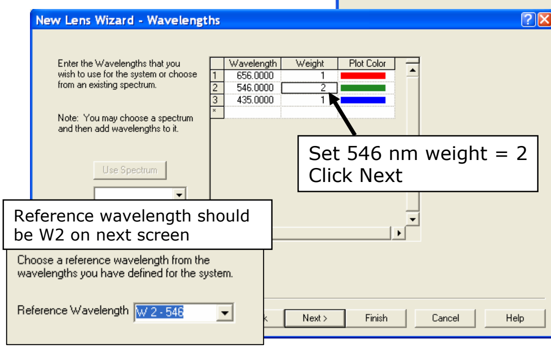
Note that each patent lens file includes a lens drawing, and this one shows three defined field angles

O P T I C A L   R E S E A R C H   A S S O C I A T E S

Defining System Data

- Pupil specification sets the light-gathering power of the system and can be defined in several ways





- At least one wavelength must be defined, and up to 21 are allowed, always entered in nanometers

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O P T I C A L   R E S E A R C H   A S S O C I A T E S

Field Definition

- "Field of View" (FOV) describes the size of the object or image that a lens can handle
  - If the object is at infinity, angular measure is used
  - For finite object distances, object or image height can be used, with a slight preference for object-side definitions
- CODE V performs calculations at discrete field points defined with the lens
  - In many cases, 3 field points are used, though some systems are designed for "axis only" with a single field
  - Designers often use additional field points for wider angle systems, and we will add an additional field point to this lens

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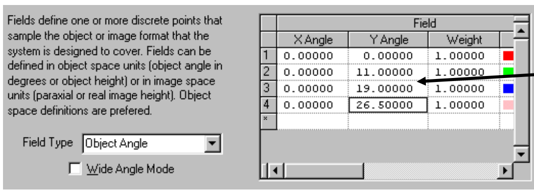
NLW Spec Data

- On the Fields page, right-click on field 2 and choose **Insert** from the shortcut menu. (Inserting before field 2 retains the pre-defined vignetting for the larger fields.)



Enter 0, 11, 19, and 26.5 (degrees) for the Y Angle semi-FOV values of field points F1 to F4

- Click **Next>** and on the last page, click **Done**.

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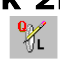
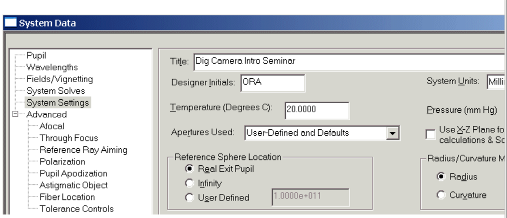
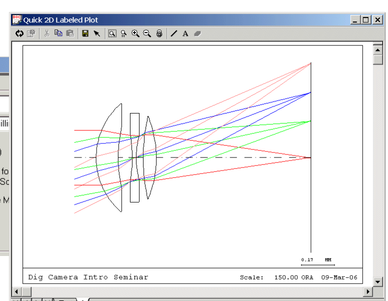
Titles and Pictures

- Choose the **Lens > System Data** menu
  - Click on **System Settings** item
  - Enter new title, **Dig Camera Intro Seminar**
- Click the **Quick 2D Labeled Plot** icon to make a lens picture 





(Leave this window open for later re-draws)

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The LDM Spreadsheet

- The LDM spreadsheet contains the basic surface data
  - Surface numbers, names (user labels), types, Y Radius of Curvature or Y Curvature (depends on **Edit > Radius Mode** setting), thickness (distance to next surface), glass name, refract mode (usually Refract or Reflect), aperture size
  - Right click on any cell and choose **Surface Properties** to get more surface information

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	0.3561	0.1100	786500.	Refract	0.2062 O
2		Sphere	0.7012	0.0700		Refract	0.1683 O
3		Sphere	-0.6597	0.0200	717360.	Refract	0.1329 O
Stop		Sphere	0.4168	0.0350		Refract	0.1088 O
5		Sphere	0.9208	0.0650	834810.	Refract	0.1408 O
6		Sphere	-0.5408	0.7743 S		Refract	0.1521 O
Image		Sphere	Infinity	-0.0040		Refract	0.4719 O
End Of Data							

Surface Details

- Values in cells can be edited, including copy and paste
- The status of a cell is indicated by a small status indicator (e.g., V for variable)
  - You can change the status by right clicking and using the shortcut menu
- Cells that are gray are defined indirectly (e.g., solves, default apertures, pickups) and cannot be edited
  - You can still right-click these values to change their status
- Right-click on a cell and choose **Surface Properties** to see all information (e.g., right click on the thickness of surface 6, the gray cell with S for solve)...

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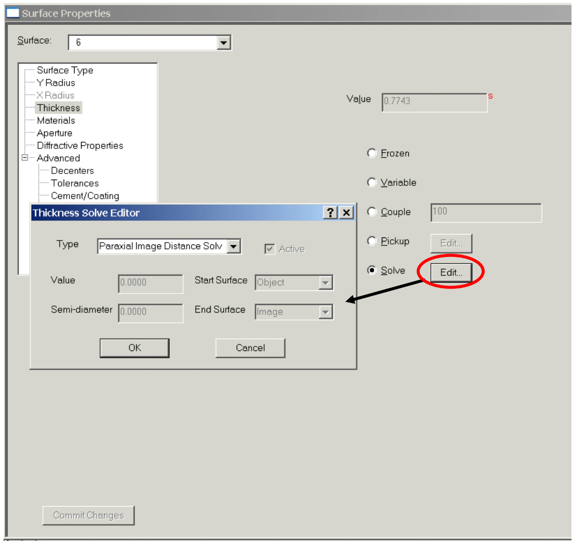
Surface Properties



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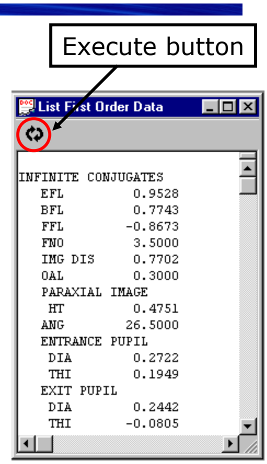
First Order Properties

- The required effective focal length (EFL) is 6 mm
- To display first order data including EFL
  - Choose **Display > List Lens Data > First Order Data**
  - Current value is 0.9528 mm
  - The Execute button updates the window
  - You can also place EFL on the Status Bar for continuous updates (**Tools > Customize**)



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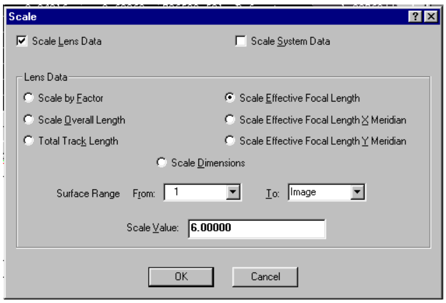
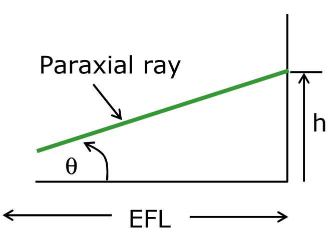
Scaling the Lens

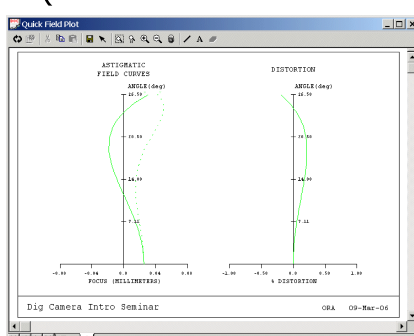
- Select surfaces 1 to the image in the LDM spreadsheet
- Choose the **Edit > Scale** menu
  - Note that the surface range you selected is displayed
  - In the dialog box, click the **Scale Effective Focal Length** button, and enter the desired EFL (**6.0**) as the Scale Value, then click **OK**.



Analyze Distortion

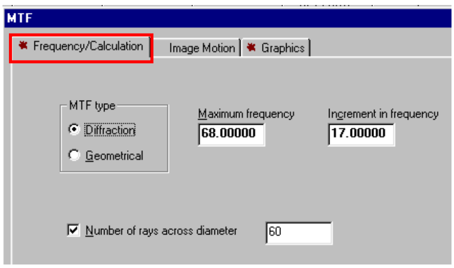
- Distortion is the variation of image height from the idea paraxial height, h = (EFL)* (tan θ)
  - Click the **Quick Field Plot** toolbar button
- The left curve is astigmatism vs. field angle, the right curve is distortion (about 0.2% maximum)

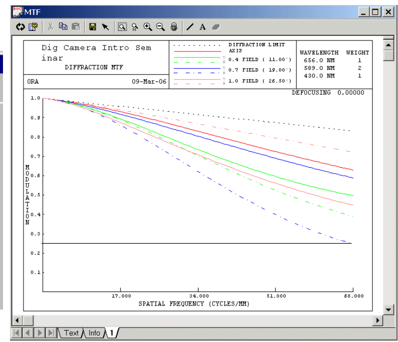




Analyze MTF

- MTF is related to resolution or "sharpness"
  - Choose **Analysis > Diffraction > MTF**
  - Frequency **68** (cycles/mm) for maximum, **17** for increment
  - On Graphics tab, enter **68** for maximum plot frequency
  - Click **OK** — MTF is above 0.25 for all fields.

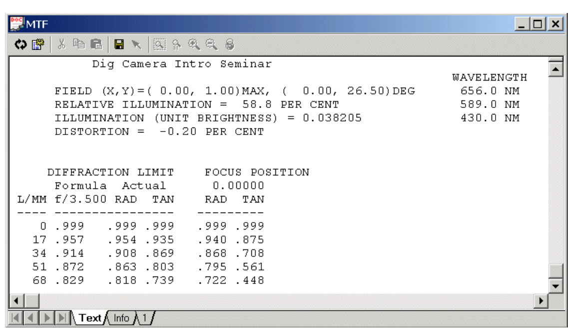




Vignetting/Illumination

- Vignetting is the clipping of off-axis beams by apertures other than the stop
  - Can be a problem or a solution (depends on specs)
  - Non-zero vignetting reduces off-axis illumination
- Relative illumination includes vignetting effects

MTF text output includes relative illumination for each field (58.8% for the starting lens full-field)



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Other Issues

- This lens is very small – with focal length and detector size around 6 mm (about 0.25 inch)
  - The center element has a thickness of 0.126 mm, too thin for practical fabrication
  - Need to consider practical aspects of small elements, including thickness constraints in optimization
- Would also need to consider glass properties
  - Patent lens has "fictitious" (variable) glass with high index of refraction
  - Higher index glasses are more expensive
  - May want to constrain glass to lower index

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Workshop 2-1: Telephoto Lens

- A telephoto lens has a total length from first vertex to image plane that is less than the effective focal length.
- We're going to design a 135-mm focal length, *f*/3.5 telephoto lens for a 35-mm single-lens reflex (SLR) camera. Design target is MTF > 0.5 at 30 cycles/mm, and MTF > 0.2 at 60 cycles/mm.
- Use the New Lens Wizard to restore the CODE V Sample Lens called TELEPHOT.
  - Change the Pupil Specification to **Image *f*/number** and enter **3.5** as the value.
  - Don't change the wavelengths or weights.
  - Change the Field Type to **Paraxial Image Height** and enter Y values of **0**, **15.3**, **21.63**.
  - Don't alter the vignetting.

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Workshop 2-1: Telephoto Lens (2)

- Draw the lens.
- Use **Edit > Scale** to scale the lens data by a factor of 1.35. Make sure you scale all surfaces (1 through Image).
- Verify the effective focal length using **Display > List Lens Data > First Order Data**.
- Compute the diffraction MTF with a maximum frequency of 60 and increment of 5.
- Save the lens for future use.

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Optimization

- Optimization is used to improve the optical quality of a starting design
  - Requires variables, parameters that can be altered
  - Requires an error function, a quantity that correlates with quality (smaller is better, zero is "perfect")
  - Requires constraints, or boundary conditions
- CODE V's optimization is called Automatic Design
  - Uses a constrained damped least squares (DLS) method
  - Provides a sophisticated default error function and other intelligent defaults
  - User can re-define everything, including the error function

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Optimization Plan

- Use LDM to define variables
  - All curvatures, all thicknesses, all glasses
- Define general constraints on thickness and glass
- Define a specific constraint on EFL, others as needed
  - Distortion may require a constraint
- Draw the lens at each cycle
- Optimize with default weights
- Analyze MTF and distortion
- Re-optimize with field weights adjusted to balance performance across fields

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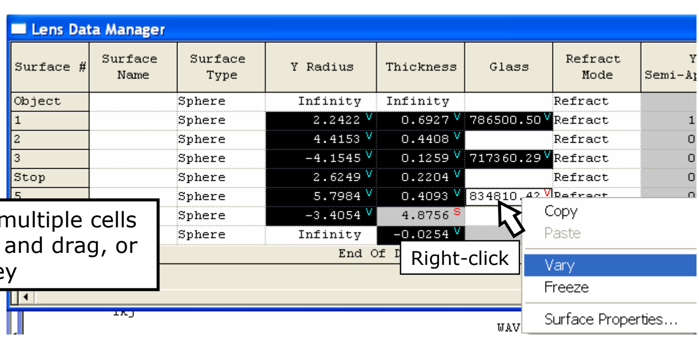
Define Variables

- Vary radii of surfaces 1-6,
- Vary thickness of surfaces 1-5 plus image thickness
  - Don't vary thickness of 6 (it has a PIM solve)
- Vary all glasses (converted to fictitious glass)



* Highlight multiple cells by left-click and drag, or use CTRL key

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Variable glasses must be fictitious

- Fictitious glass is defined by its index (Nc) at a central wavelength and its Abbe (V) value at two extreme wavelengths (typically d, F, & C wavelengths)
  - V = (Nc-1)/(Ns – NL)

Where:
Nc = index at central wavelength
Ns = index at short wavelength
NL = index at long wavelength
Dispersion = (Ns – NL)

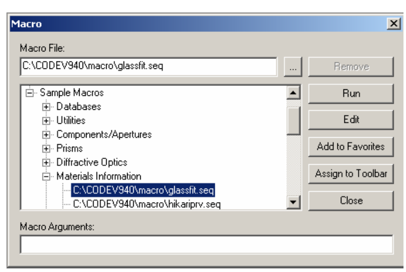
- Two different formats are supported

1.5168:64.17
- or -
5168.6417
→
n = 1.5168
V = 64.17

Optimizing with fictitious glass

- Default is to vary both index and dispersion (typical use)
  - Use **Reviews > Variables & Couplings** to vary only the index, only the dispersion, or constrain the glass to always lie on a defined boundary of a glass map

- After optimization, fictitious glasses can be converted to real glasses with the help of the CODE V sample macro GLASSFIT.SEQ



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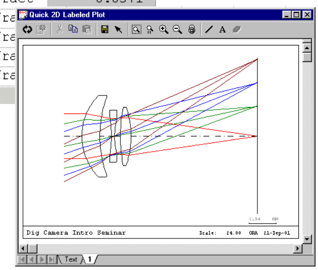
Pre-AUTO Lens

- The LDM spreadsheet shows the values, variables, and paraxial image solve
- **Quick 2D Labeled Plot** shows starting form

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	2.2422 V	0.6927 V	786500.5010 V	Refract	1.2987 O
2		Sphere	4.4153 V	0.4408 V		Refract	1.0595 O
3		Sphere	-4.1545 V	0.1259 V	717360.2950 V	Refract	0.8371 O
Stop		Sphere	2.6249 V	0.2204 V		Refra	
5		Sphere	5.7984 V	0.4093 V	834810.4290 V	Refra	
6		Sphere	-3.4054 V	4.8756 S		Refra	
Image		Sphere	Infinity	-0.0254 V		Refra	
End Of Data							



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Variables Ready for AUTO

- It’s good to review your variables before optimization
- Choose the **Review > Variables and Coupling** menu

Variables and Couplings

Commit

	Surface #	Parameter	Glass Sub-Parameter	Coupling Code
1	1	Curvature		0
2	1	Thickness		0
3	1	Glass 1	Index and Dispersion	0
4	2	Curvature		0
5	2	Thickness		0
6	3	Curvature		0
7	3	Thickness		0
8	3	Glass 1	Index and Dispersion	0
9	Stop	Curvature		0
10	Stop	Thickness		0
11	5	Curvature		0
12	5	Thickness		0
13	5	Glass 1	Index and Dispersion	0
14	6	Curvature		0
15	Image	Thickness		0
End Of Data				

A “Coupling Code” of 0 means “vary,” while 100 means “freeze,” though frozen parameters are not shown in the review spreadsheet.

Automatic Design Settings

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- Automatic Design is an incredibly flexible design tool
  - Requires a ray-traceable starting lens with one or more variables (done in LDM)
  - Provides several different built-in error functions, plus user-defined error functions
  - Provides many types of constraints to set requirements, plus user-defined constraints
  - Runs local optimization by default, but very effective Global Synthesis optimization can be used with a single click
- Input dialog is divided into a number of tabs

General Constraints Tab

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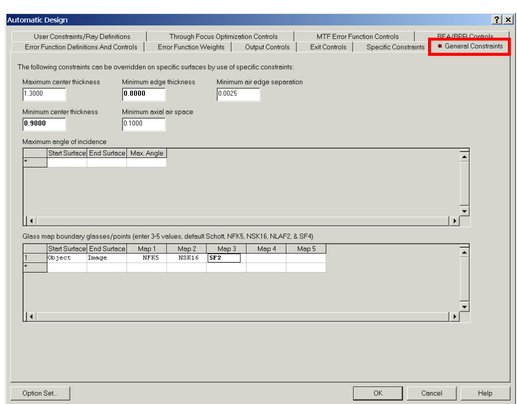
- General constraints prevent non-physical solutions (e.g., negative edges, glass with n = 99)
  - They apply to all surfaces and zoom positions, but can be overridden by specific constraints

Enter **0.9** for minimum center thickness, and **0.8** for minimum edge thickness (keep other defaults).
Delete glass SF4 and change Map 3 glass to **SF2**.



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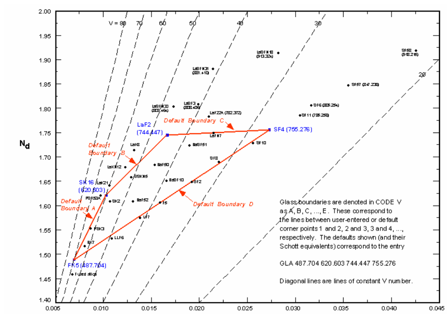
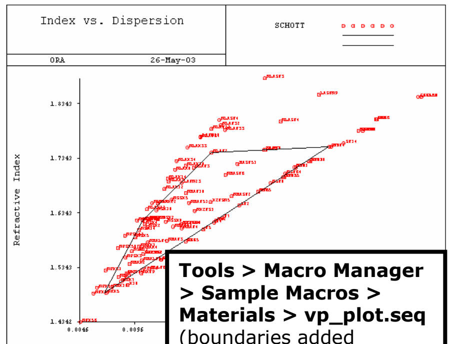
The Glass Map

- The optimization glass map is defined on an index vs. dispersion (N_F - N_C) plot
  - The default glass map boundaries form a 4-sided polygon containing most real glasses with reasonable cost



Default boundaries (RM p. 17-32)



Tools > Macro Manager > Sample Macros > Materials > vp_plot.seq (boundaries added separately)

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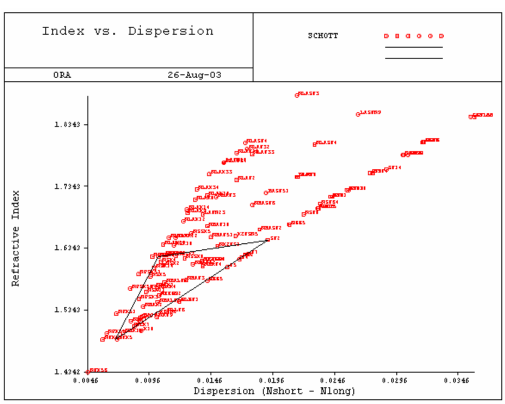
The Glass Map

- Making this a smaller 3-sided polygon can restrict variable glasses to a lower index region of generally less expensive glass types
  - Use SF2 to define the 3rd vertex



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Specific Constraints

- Specific constraints are boundary conditions imposed by you, to force the optimizer to maintain requirements
  - Most common specific constraint is EFL or another scale-holding constraint, as shown in first example
  - There are many things you can constrain, divided into 8 categories (optical, manufacturing, real ray, etc.)
  - Constraints can be held to a value (=), bounded (> or <), minimized, or only displayed
- Try to use the minimum necessary constraints
- In this case, EFL is needed, others may be added later

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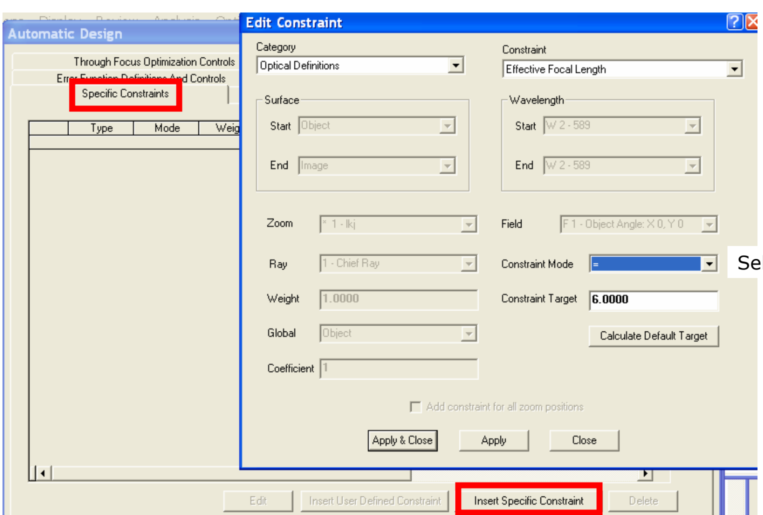
EFL Constraint Entry

– Enter equality constraint, EFL = 6 mm



Select "="

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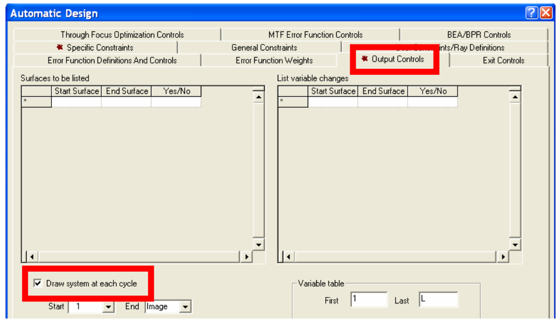
Other Settings

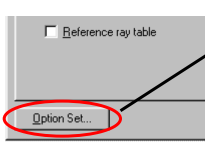
- Drawing the lens on each cycle is often useful (Output Controls)

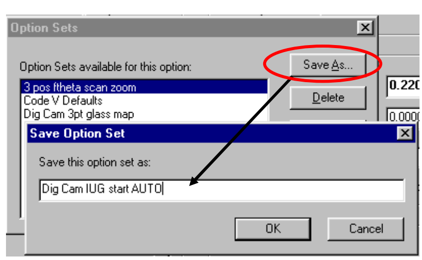


- Common changes for optimization,
  - Type of error function
  - # of rays traced, ray grid control
  - Exit controls (max cycles, improvement %, interactive)
  - Weights on error function components
  - Global synthesis

Option Sets

- Settings entered in any option input dialog are saved for the current CODE V session
  - As long as you keep the output window open, you can use the Modify Settings button to view and change settings
- To save the settings for a future session, click the **Option Set** button, then use the **Save As** button





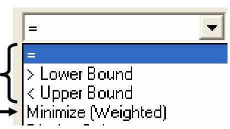
The Error Function

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

Usually sufficient (weighted transverse ray aberrations; wavefront variance)

Must start with good system (MTF; fiber coupling efficiency; user-defined)

- Contains only image errors in the default case
  - Constraints are handled separately (Lagrange multipliers)
  - Constraints can be included with aberrations (weighted)
    - Unnecessary for most constraints
    - Can be useful for non-linear constraints (e.g., distortion)



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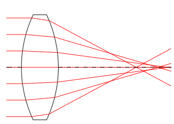
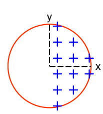
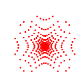
Default Error Function







- Default error function is a weighted RMS spot size
  - Transverse ray aberrations used (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 factors are 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)

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AUTO Output Header

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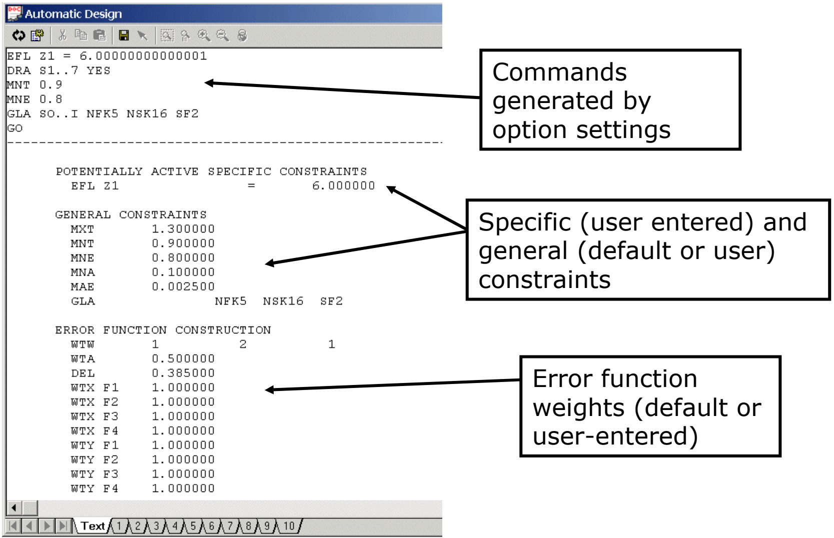

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Per-cycle Output

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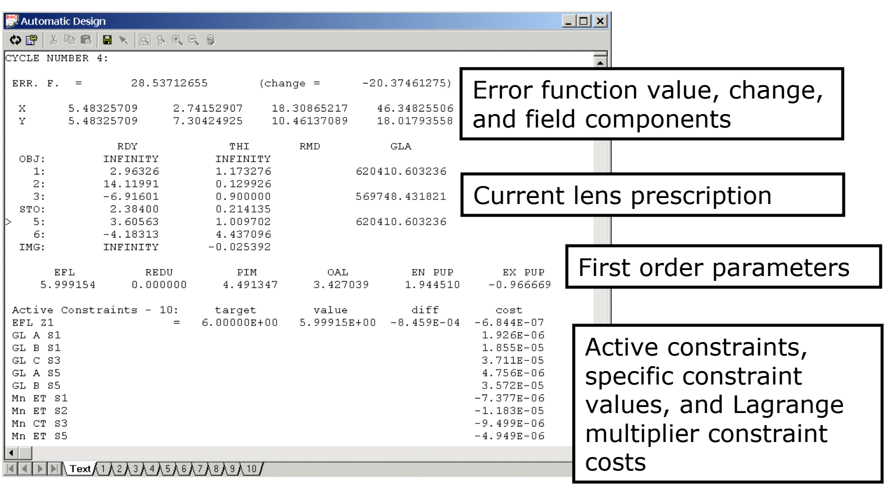

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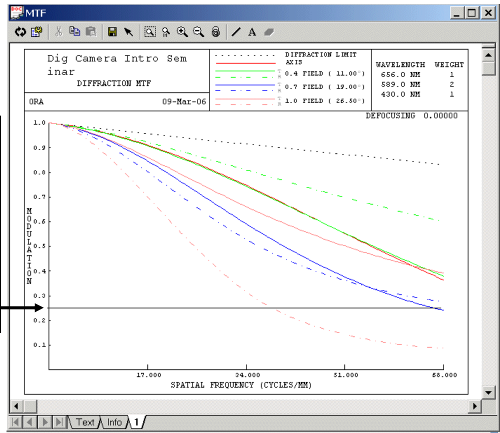
Analysis

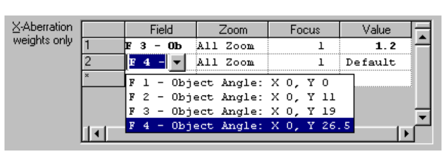
- Re-run **MTF** and **Quick Field Plot** windows
  - Distortion (full field) is about -2.6% (4% allowed)
  - MTF at 51 lp/mm is below 25% for some fields

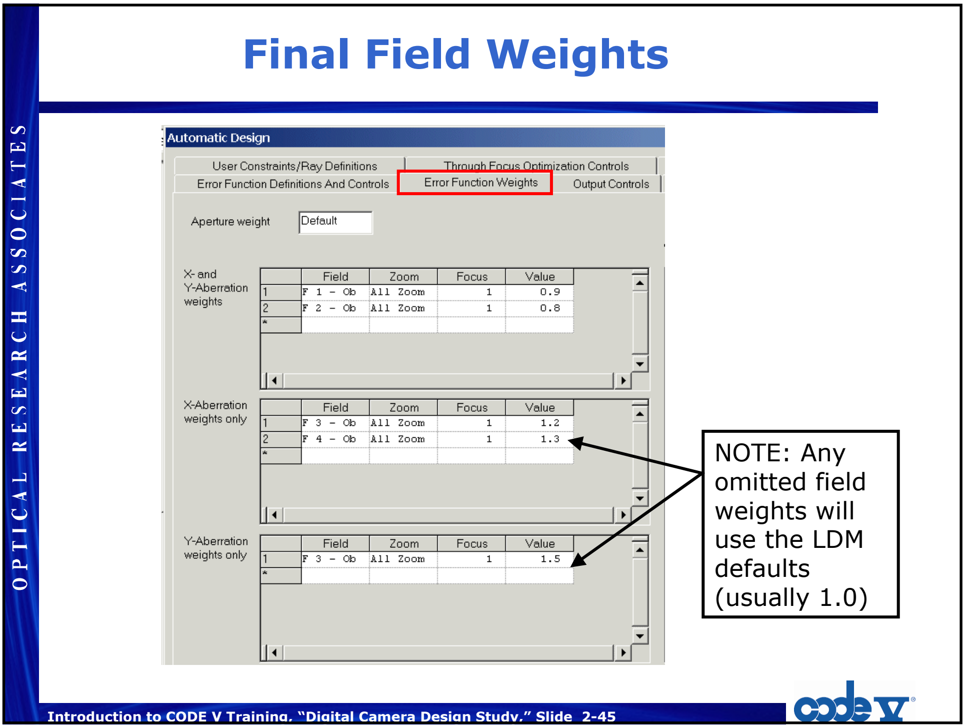
Weighting field components in AUTO, possibly independently in X and Y, can most likely shift the solution to bring all curves above 25% line



Weights and Constraints

- Error function weights have strong effect on solution
  - Frequently determined by trial and error, based on analysis results and with use of **Edit > Undo** if a trial solution is very bad
  - Field weights have X and Y components
- Weights are found on the Error Function Weights tab
  - Example below is for the X components of field weights
  - Next slide shows a set of weights that work pretty well for this case




Final Field Weights
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Automatic Design
User Constraints/Ray Definitions
Through Focus Optimization Controls
Error Function Definitions And Controls
Error Function Weights
Output Controls
Aperture weight
Default
X- and Y-Aberration weights
Field Zoom Focus Value
1 F 1 - Ob All Zoom 1 0.9
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
NOTE: Any omitted field weights will use the LDM defaults (usually 1.0)
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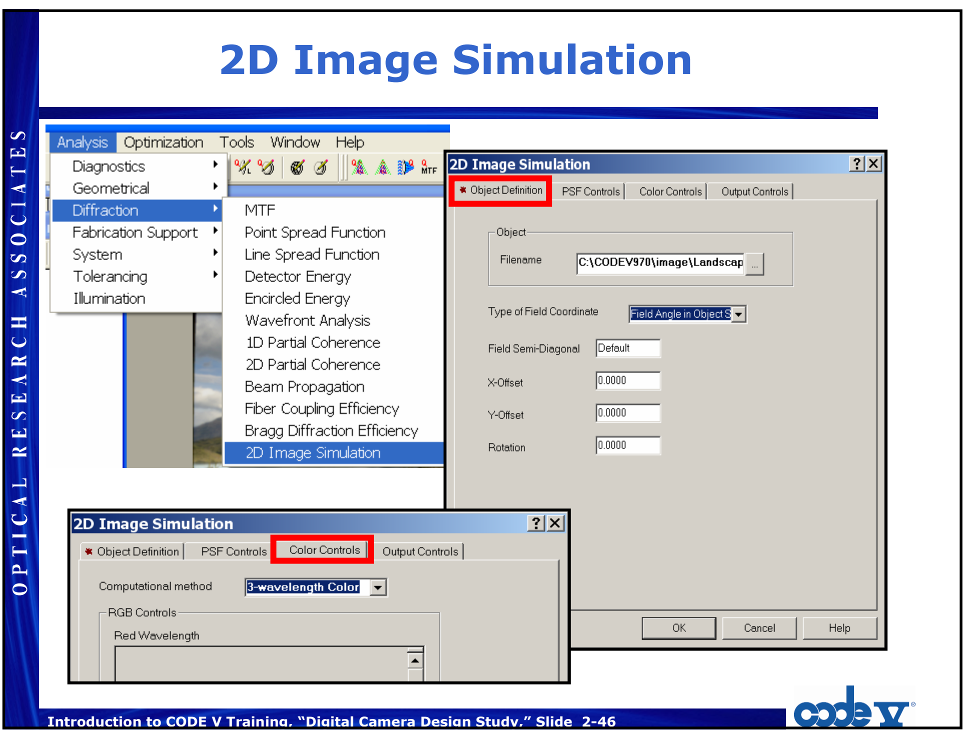
code v


2D Image Simulation
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Analysis Optimization Tools Window Help
Diagnostics
Geometrical
Diffraction
Fabrication Support
System
Tolerancing
Illumination
MTF
Point Spread Function
Line Spread Function
Detector Energy
Encircled Energy
Wavefront Analysis
1D Partial Coherence
2D Partial Coherence
Beam Propagation
Fiber Coupling Efficiency
Bragg Diffraction Efficiency
2D Image Simulation
2D Image Simulation
Object Definition PSF Controls Color Controls Output Controls
Object
Filename C:\CODEV970\image\Landscap
Type of Field Coordinate Field Angle in Object S
Field Semi-Diagonal Default
X-Offset 0.0000
Y-Offset 0.0000
Rotation 0.0000
OK Cancel Help
2D Image Simulation
Object Definition PSF Controls Color Controls Output Controls
Computational method 3-wavelength Color
RGB Controls
Red Wavelength
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code v

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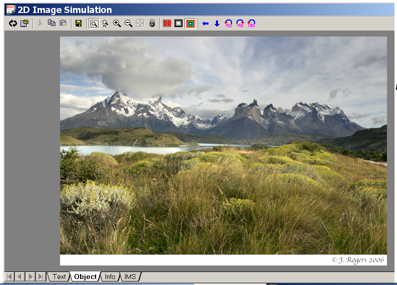
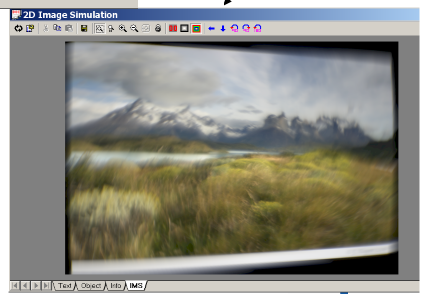
2D Image Simulation (cont.)

Original Picture



Image@focus

Image tilted 10°
in XZ plane



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Conclusions - NLW/AUTO

- The New Lens Wizard provides a step-by-step method for generating starting points from previous work
  - You can change system data in the NLW
  - You will usually need to also change things such as variables in the LDM
- Automatic Design is a flexible method for improving the performance of a starting design
  - Multiple error function types are supported
  - General and specific constraints allow detailed control of boundary conditions

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Workshop 2-2: Optimize Telephoto Lens

- Prepare the lens for optimization by adding additional variables in the LDM:
  - All curvatures (except object, stop and image) are currently variables
  - Select all thicknesses from surface 1 through 9 and make them variables
  - Vary the (flint) glasses on surfaces 4 and 9
- Optimize with 1 constraint: EFL = 135. Draw the lens at each cycle.
- Compute the diffraction MTF with a maximum frequency of 60 and increment of 5. You should have on-axis MTF > 0.5 at 60 cycles/mm.

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Workshop 2-2 : Optimize Telephoto Lens (2)

- A telephoto lens should be shorter than its focal length (S1 to image < EFL). Reoptimize with a constraint to keep the Overall Length (under "Manufacturing/Packaging") from **surface 1 to the image < 120**. (** Note: The First Order Data lists the overall length from S1 to S(I-1) as "OAL.")
- Re-compute the MTF. Did it change much?
- An SLR lens must have an image distance (back focal length, BFL) > 40 mm. Reoptimize with this constraint, found under "Optical Definitions." Did it change the MTF?
- The rear element semi-diameter is somewhat large for a typical SLR lens mount. (A typical SLR mount requires a semi-diameter < 12.5 mm.) See how small you can make it while keeping the on-axis MTF > 0.5 at 30 cyc/mm. Use the Max Semi-diameter constraint found under "Manufacturing/Packaging" at surface 10.

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Tolerancing Basics

- Tolerance analysis is an important step for any design that will be fabricated
- The goal is to identify and simulate possible fabrication errors and predict their effects
  - Ideally this should be done in terms of measurable quality criteria such as MTF, RMS wavefront error, or coupling efficiency
  - Should also simulate the effects of assembly or end-use adjustments (compensators)
- CODE V has several tolerancing features

Tolerance Analysis Functions

- TOR is CODE V's primary option for calculating the effects of manufacturing and assembly errors on MTF, RMS wavefront error, fiber coupling efficiency, or polarization dependent loss
  - The name TOR comes from Tolerancing, Ray-based (as opposed to paraxial-based tolerancing)
  - It uses a very fast algorithm that provides information about individual tolerance sensitivities (i.e., performance drivers) and it accurately predicts system performance
  - Many of the details of TOR will be discussed in the *Introduction to Tolerancing* section

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Tolerance Analysis Functions

- CODE V has other tolerancing options
  - TOL – tolerance first-order and third-order properties
  - TOD – tolerance on chief ray distortion
  - TOLFDIF – macro for finite-difference tolerancing using user-defined performance measures
  - TOLMONTE – macro for Monte Carlo tolerancing using user-defined performance measures
- These other tolerancing options will not be covered this week

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Fab & Assembly: What Can Go Wrong?

- Murphy's Law in action
  - Anything that can go wrong WILL go wrong
  - No physical device can be built perfectly, so possible errors must be anticipated and simulated
  - The greater the required precision, the greater the cost
- Typical tolerances (partial list)
  - Test plate fit (DLF) – measures surface shape error
  - Thickness (DLT) – measures glass or air thickness
  - Index and dispersion (DLN, DLV) – glass errors
  - Surface tilt is usually measured as wedge (TIR = total indicator runout)
  - Barrel tilt (BTI) measures the tilt of an element or group

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Compensators

- Compensators simulate adjustments made during assembly or alignment
  - Compensators minimize loss in performance
  - They are not allowed to improve the performance by themselves but only to minimize performance loss
  - Compensation is done simultaneously over field and zoom (by default)
  - Compensation can be done separately for each field and zoom
- Any tolerance parameter can be a compensator
  - Most compensators relate to moving an element or group of elements (shift along Z, tilt, decenter, etc.)
  - Default compensator is shift of the image surface (DLZ SI)

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Statistics

- Tolerances specify the plus and minus limits that are possible around a nominal value (range)
  - You try to achieve the nominal value, but the as-built values will be randomly scattered within the range
  - Therefore each unit you build is slightly different
- Performance prediction requires statistics
  - You want to know the yield (percentage of as-built systems with acceptable performance) or probability of success for unit-one systems
  - Such predictions can be obtained from Monte Carlo simulation, or from simulated Monte Carlo based on assumption of large number (> 10) tolerances

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Inverse vs. Sensitivity Mode

- Sensitivity analysis means taking a set of assumed tolerance values and predicting their performance effects
  - This requires a way to determine the assumed tolerances
  - Could be based on fabrication capability (or guess work)
- Inverse sensitivity means determining tolerance values that cause a certain performance change
  - This is done for each tolerance, scaling so that each tolerance causes the same small drop in performance
  - Limits and rounding are applied to the values to make sure they are realistic, so in practice, not all tolerances will contribute the same error

Default Tolerance Run Input

- Tolerances are associated with surfaces and are thus defined in the LDM as part of lens data
  - You can define tolerances in great detail, for individual surfaces or groups of surfaces
- If you run TOR without defining tolerances, a default set is defined for you
  - It includes all the basic surface tolerances plus group tolerances for single elements and cemented elements
  - This is often a good starting point, but it does not contain group tolerances for non-cemented sub-assemblies, since CODE V does not know the mount structure of a lens

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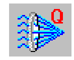
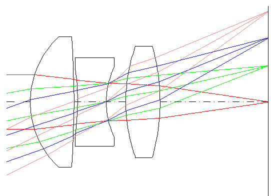
Prepare the Lens

- Place the lens at best focus by clicking the Quick Best Focus button on the tool bar 
  - TOR works best when the lens is at best focus
  - Quick Best Focus runs the RMS Wavefront Analysis option and sets the image surface thickness for best focus



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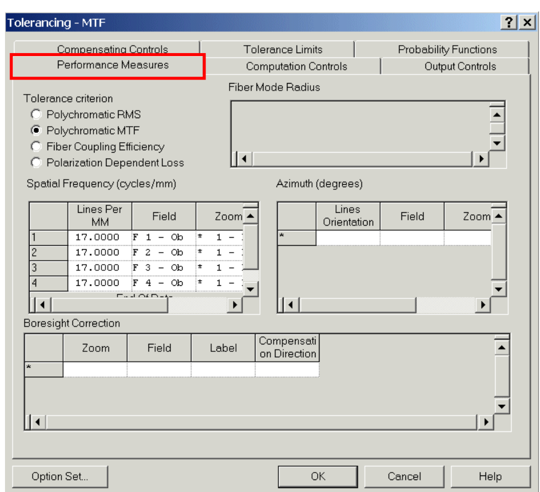
Run MTF Tolerance Analysis

- Choose **Analysis > Tolerancing > MTF**
- In the dialog, enter **17** for the Spatial Frequency for each of the four fields (Lines per MM column)
- Click **OK**.



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Tolerance Output

- TOR generates significant output, including:
  - Tolerance sensitivity tables for each field and zoom showing the performance change with compensated plus and minus tolerance change
  - A performance summary table for each field
  - If CODE V is determining the tolerance set (inverse sensitivity mode), two tables of tolerance values are printed (centered & decentered tolerances)
  - A final 2-Sigma (98% probability) performance summary for all fields and zooms
  - A cumulative probability plot

All of this output will be covered in detail in the *Tolerance Analysis* section

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Example Output

Tolerancing - MTF

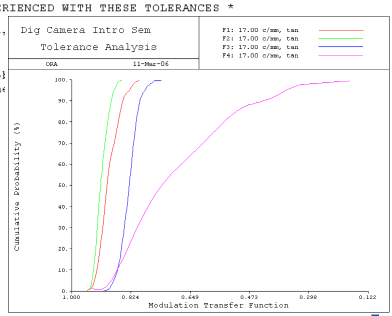
RELATIVE FIELD	FREQ L/MM	AZIM DEG	WEIGHT	DESIGN	DESIGN + TOL *	COMPENSATOR RANGE (+/-) DLZ S7
0.00, 0.00	17.00	TAN	1.00	0.9006	0.8234	0.165557
0.00, 0.39	17.00	TAN	1.00	0.9186	0.8660	0.165557
0.00, 0.69	17.00	TAN	1.00	0.8338	0.7576	0.165557
0.00, 1.00	17.00	TAN	1.00	0.8777	0.3036	0.165557

* NOTE - A SUBSTANTIAL LOSS IN MTF HAS BEEN EXPERIENCED WITH THESE TOLERANCES *

* The probable change and cumulative prol
assumption that the distribution of the

Spec:
F1, F2: MTF > 0.90
F3, F4: MTF > 0.85

Performance Summary Table & Graph



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Review > Tolerances (LDM)

Tolerances and Compensators

Commit | Fringe Wavelength 546.1000 | Autofill... | Delete All

Tolerances

	Type	Start Surface	End Surface	Label	Value	Freeze	X
26	CYD - Irregularity Oriented 45 Degr	3	3		0.5000	☐	
27	CYD - Irregularity Oriented 45 Degr	Stop	Stop		0.5000	☐	
28	CYD - Irregularity Oriented 45 Degr	5	5		0.5000	☐	
29	CYD - Irregularity Oriented 45 Degr	6	6		1.5000	☐	
30	CYN - Irregularity Oriented 0 Degre	1	1		0.5000	☐	
31	CYN - Irregularity Oriented 0 Degre	2	2		0.5000	☐	
32	CYN - Irregularity Oriented 0 Degre	3	3		0.5000	☐	

Compensators

	Type	Start Surface	End Surface	Label	Value	Compensator or Use Control	X O
1	DLZ - Surface Z-Displacement (lens un	Image	Image		20.0000	May be us	

End Of Data

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Special Features

- CODE V has many special features not shown in this example, including
  - Zoom (multi-configuration set-up)
  - Tilted and decentered systems
  - Non-spherical surfaces
  - Solves and pickups
  - Gradient-index (GRIN) materials
  - Polarizers and birefringent elements
  - Diffractive surfaces

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