Chapter 2

Just Do It: Design a Digital Camera Lens

In this chapter, you will design a fixed-focus digital camera lens for VGA resolution (640 x 480). Guided by the required specifications, you will use the New Lens Wizard to identify a suitable starting point. You will then modify, analyze, and optimize the optical system to meet the requirements. This will allow you to learn most of the basic techniques needed to use CODE V.

Contents

Learning by Doing

A Simple Digital Camera Lens

Digital cameras are very common these days, and the latest mega-pixel models have high-resolution CCD arrays and sophisticated optics and electronics. But don't worry, that won't be your very first task with CODE V. Instead, you will design a fairly simple objective lens for a fixed-focus digital camera. This will still require some optical design, but it's a relatively simple problem, a two- or three-element centered lens with glass and/or plastic refracting lens elements.

Here is what you will learn in this chapter:

- Interpret general design specifications for a simple lens
- Use this information to identify a starting point
- Modify the starting point to match the requirements
- Perform a basic analysis, compare these results with the specs, and determine guidelines for optimization

In the next chapter, you will use the results of this chapter as a starting point to

- Optimize the lens
- Identify problems with the design for potential refinement

These steps will allow you to work with many of CODE V's features through various phases of optical design. We will explain some of these features as they are introduced here, with additional explanations in subsequent chapters.

Design Specifications

Sometimes you will receive a lens prescription from someone and you will need to enter it in CODE V, analyze it, and perhaps optimize it. This is fairly straightforward. In other cases, a design problem starts out with a spec, or set of specifications, on how the lens must perform, and from these guidelines you must determine a starting point, set it up, analyze, and optimize it.

For this digital camera problem, the spec came from a CODE V customer who makes consumer products. The question was, "If you wanted to define a low-cost, fixed-focus digital camera for VGA, how would you specify it?"

Fixed-focus VGA Digital Camera Objective Specifications

- Small number 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 (2.5 ft.) to infinity
Focal length	Fixed, 6.0 mm
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

What Does It All Mean?

For one thing, this means that it will be a rather small lens system. The sensor size and the focal length of the lens are each only 6 mm (about a quarter of an inch). The sensor size and the effective focal length (EFL) will establish the field of view (FOV) for the lens according to the infinite-object-distance relationship, $h = f \tan \theta$ or

Image height = EFL * tan(semi-FOV)

In this case, the image height is 3 mm (half of the detector diagonal), and the EFL is 6 mm, so you can solve this for the semi-FOV of 26.5° (this is useful since the patent database lenses are listed by f/number and semi-FOV). Given that you want a small number of elements, this is all the information you need to find some starting points.

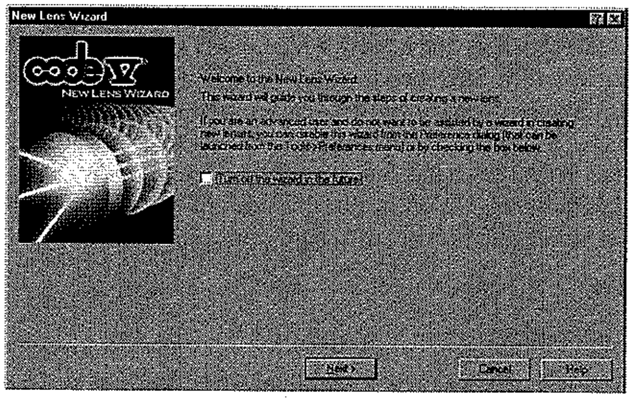
CODE V has analysis features to allow evaluation of the other specs (distortion, MTF, relative illumination, transmission). We will introduce most of these features later, as they are needed, but consider the term *sharpness* for a moment. Sharpness is often defined by MTF, which quantifies the lens' ability to image information as a function of spatial frequency. Maximum sharpness is given by an MTF of 1.0. Minimum sharpness (i.e., no information) occurs for an MTF of 0.0. High spatial frequencies represent small details and are measured in lines per millimeter. We will discuss MTF and other evaluation methods in more detail later.

A digital camera uses a CCD array consisting of small but finite-sized cells called pixels (there are actually three color pixels for each cell, but for design purposes, we will think of each cell as consisting of a single pixel). The spec indicates that the pixel size is 7.4 microns square. The maximum spatial frequency that this array will resolve can be calculated as one over twice the pixel size, 1/(2*0.0074) = 67.6 lines/mm. With this CCD array, any image information with a higher spatial frequency (i.e., finer detail) than this will not be seen. In spite of this, the optics must actually have non-zero MTF somewhat beyond the CCD cutoff frequency, so the combined optics/detector MTF will produce a usable contrast up to the CCD cutoff frequency. This is the meaning of the small table on page 19 under the Sharpness specification.

The New Lens Wizard

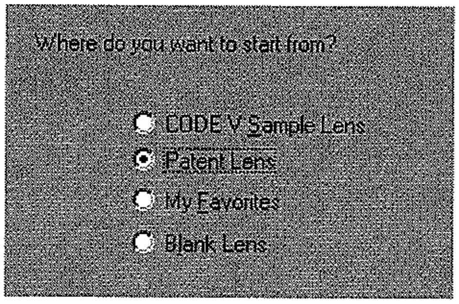
Starting a New Lens

The New Lens Wizard is a tool for creating new optical system models from existing designs (samples, patents, or your own saved favorite lenses) or from scratch. It helps you to locate a suitable starting point and then define the essential system data corresponding to your specifications (including pupil size, wavelengths, and field data). Start CODE V and launch the New Lens Wizard now:



Welcome to the New Lens Wizard

1. Choose the **File** > **New** menu.
2. Click the **Next** button on the Welcome screen.
3. Click the button labeled **Patent Lens** and click the **Next** button.



Where do you want to start from?

○ CODE V Sample Lens
● Patent Lens
○ My Favorites
○ Blank Lens

Patent Database

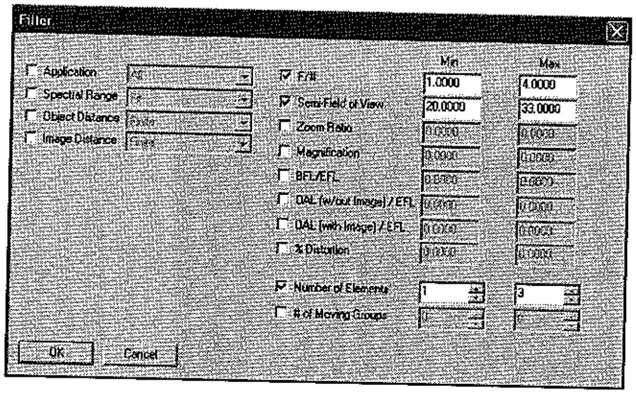
In addition to some 30 sample lenses that demonstrate program features, CODE V includes a database of some 2,456 expired patents (mainly centered optical systems for various applications). You can use the New Lens Wizard or the Patent Lens Search feature (**Tools > Patent Lens Search** menu) to access and search this database through the use of filters that specify various properties. In the following procedure, you will continue using the New Lens Wizard to select a patent lens.

1. In the New Lens Wizard, click the **Filter** button.

   The **Filter** dialog box displays, which allows you to narrow down the search for a starting point. In the case of the digital camera lens, you need both a relatively fast (small) f/number and a fairly wide field of view or field angle (26.5° semi-field angle, which corresponds to the 3 mm half-diagonal of the CCD array). You also want this lens to be fairly cheap, so it should have a small number of elements (1-3). You can fill in the filter dialog to start the search. It's a good idea to expand the range slightly since you can often slightly modify or optimize a system to the needed specifications. If you make the search targets too narrow, you may miss some promising design forms.

2. Click the check boxes and fill in the Min/Max entries for

   - F/# (f/number, try 1 to 4), goal is 3.5
   - Semi-Field of View (try 20° to 33°), goal is 26.5°
   - Number of elements (try 1 to 3), goal is smallest possible for low cost



Filter

☐ Application All
☐ Spectral Range
☐ Object Distance
☐ Image Distance

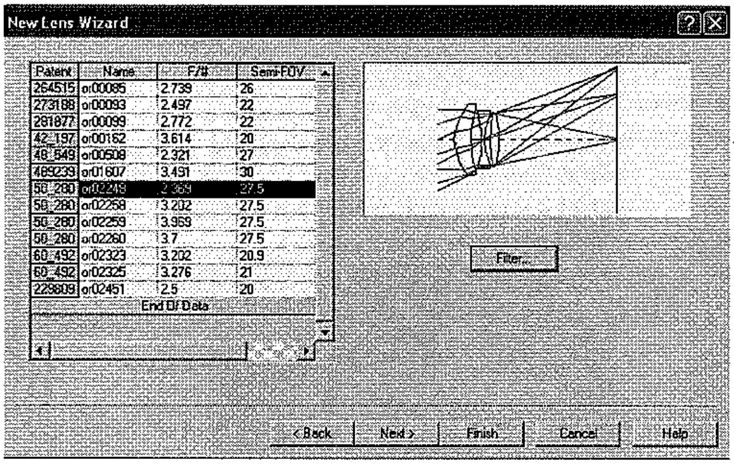
	Min	Max
☑ F/#	1.0000	4.0000
☑ Semi-Field of View	20.0000	33.0000
☐ Zoom Ratio		
☐ Magnification		
☐ BFL/EFL		
☐ OAL (w/out Image) / EFL		
☐ OAL (with Image) / EFL		
☐ % Distortion		
☑ Number of Elements	1	3
☐ # of Moving Groups		

3. Click **OK**.

   The New Lens Wizard returns you to the patent list where you will now find around 13 lenses that meet these requirements.

You could try several different starting points, but note that it will probably be hard to expand the field of view, so wider field starting points are better. The lens named **or02248** looks promising – it has a 27.5° FOV, and a faster (smaller) f/number than we need (2.4 -- this is good, since stopping down a lens to a larger f/number usually improves image quality).

4. Click the lens named **or02248** in the spreadsheet of patents.



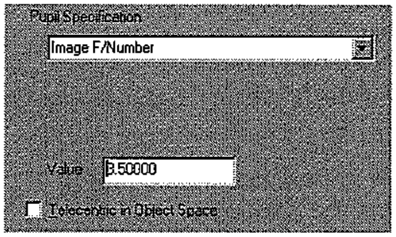
Patent	Name	F/#	Semi-FOV
264515	or00085	2.739	26
273188	or00093	2.497	22
281877	or00099	2.772	22
42_197	or00162	3.614	20
48_549	or00508	2.321	27
489239	or01607	3.491	30
50_280	or02248	2.369	27.5
50_280	or02258	3.202	27.5
50_280	or02259	3.969	27.5
50_280	or02260	3.7	27.5
60_492	or02323	3.202	20.9
60_492	or02325	3.276	21
229809	or02451	2.5	20
End Of Data			

5. Click the **Next** button to go to the Pupil page.

Defining the System Data

Now you can complete the entry of the lens through the New Lens Wizard. The next few screens ask you questions about how the lens will be used, properties that CODE V calls system data. Note that the goal at this point is to get a working model that can be modified and optimized to meet the final specs. Further changes will be needed.

1. In the New Lens Wizard, you should be on the Pupil page. Choose **Image F/Number** from the dropdown list, and enter the value 3.5.



Pupil Specification

Image F/Number

Value 3.50000

☐ Telecentric in Object Space

F/number is a ratio, so it won't need to be scaled when the lens is scaled (and the lens will most likely need to be scaled).

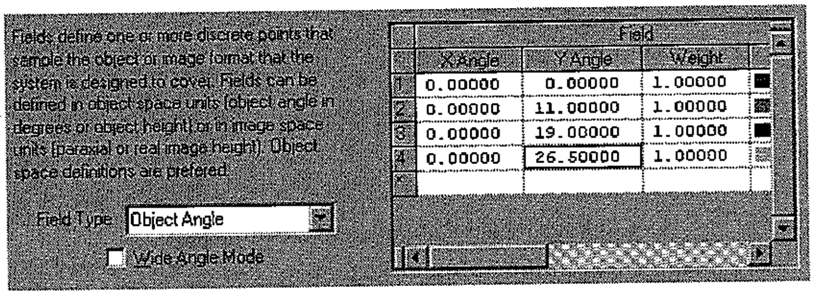
2. Click the **Next** button to go to the Wavelength page, and change the weight for the green wavelength (589.0) to **2**.

   This will give the central wavelength more emphasis later in optimization.

3. Click the **Next** button to go to the Reference wavelength page, but do not change the default value.

   This is the wavelength used for paraxial and reference-ray tracing; the default is OK.

4. Click the **Next** button to go to the Fields page. Right-click on field 2 and choose **Insert** from the shortcut menu to add an additional field angle, then type the values 0, 11, 19, and 26.5 for the four field Y angles.



Fields define one or more discrete points that sample the object or image format that the system is designed to cover. Fields can be defined in object space units (object angle in degrees or object height) or in image space units (paraxial or real image height). Object space definitions are prefered.

Field Type: Object Angle

☐ Wide Angle Mode

	Field		
	X Angle	Y Angle	Weight
1	0.00000	0.00000	1.00000
2	0.00000	11.00000	1.00000
3	0.00000	19.00000	1.00000
4	0.00000	26.50000	1.00000
*			

   This lens is fairly wide-angle in field, so adding an additional intermediate field angle is a good idea for optimization and analysis. Typically, best practice is to have fields defined at 0, 0.7 and full field at a minimum. Adding intermediate fields can be helpful in controlling zonal variation of field dependent aberrations such as astigmatism.

5. Click the **Next** button to go to the last page in the New Lens Wizard.

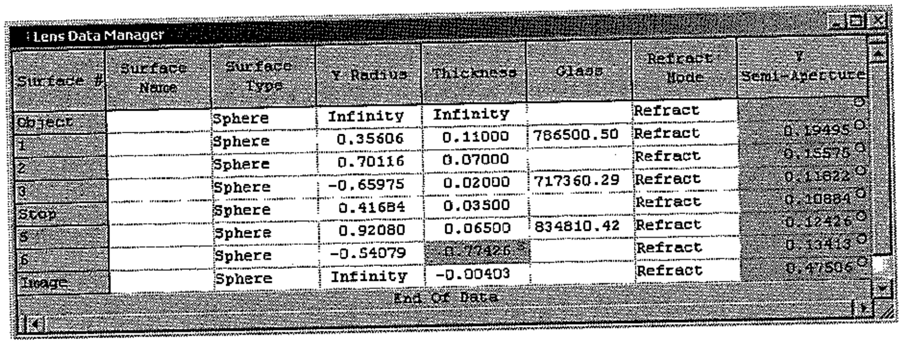
6. Click the **Done** button.

Working with Surfaces

The Lens Data Manager Spreadsheet

The basic operation of CODE V is ray tracing – everything else is based to some extent on tracing one or many rays and doing some calculations with them. In the majority of systems, rays are traced sequentially through a series of optical surfaces you have defined. The properties of these surfaces will determine how the rays are traced. This is combined with system data to create a model of the optical system.

Since surfaces are the heart of any optical model, you will spend a lot of time looking at the Lens Data Manager (LDM) spreadsheet window, which is always present in the interface (you can resize or minimize it if you don't want to see it, but you can't close it).



Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	Infinity		Refract	
1		Sphere	0.35606	0.11000	786500.50	Refract	0.19495
2		Sphere	0.70116	0.07000		Refract	0.15575
3		Sphere	-0.65975	0.02000	717360.29	Refract	0.11822
Stop		Sphere	0.41684	0.03500		Refract	0.10884
5		Sphere	0.92080	0.06500	834810.42	Refract	0.12426
6		Sphere	-0.54079	0.77426		Refract	0.13413
Image		Sphere	Infinity	-0.00403		Refract	0.47506

End Of Data

The LDM window behaves like spreadsheets in other programs in that you can resize rows or columns, select cells or groups of cells, and enter data in cells. Note that some cells are gray and do not accept data entry—these cells contain data calculated by the program and this can't be directly changed. You can right-click on any cell, including gray cells, to see a menu for that cell. Right clicking is a very common operation which gives quick access to all available information for a cell.

Tip: To see the full value of any displayed number, position the mouse pointer over the value and leave the pointer there (don't click). To change the number of displayed digits for all numbers in the interface, choose the **Tools > Customize** menu and go to the **Format Cell** tab in the **Customize** dialog box (General format with 5 digits is used in this guide). You cannot format cells individually.

Note also that in the discussion below, we are considering the default display of the LDM window for rotationally symmetric optics. It is possible to hide columns (right click any header cell) or to make certain common entries blank (e.g., Sphere and Refract; choose the **Tools** > **Preferences** > menu and go to the **UI** tab in the **Preferences** dialog box to change this). If there are non-rotationally symmetric surface properties, the LDM window will add additional columns for certain X and Y data.

Surface Details

Every lens model will start with an object surface and end with an image surface (it is really just the last surface, since not every lens model will form an image there, though most will). You will also note that there is always a surface labeled **Stop,** which is the aperture stop surface. This is defined as the limiting surface for on-axis rays. The chief ray (or principal ray) from every field point will be iterated to pass through the center (x=0, y=0) of the stop surface, unless you override this behavior with chief ray aiming (this is only necessary in a few unusual situations).

Each row in the LDM spreadsheet has a **surface number** and a **surface name** (optional but very useful in complex systems). To select an entire surface (each is displayed in a row), click the surface number. The **surface type** is next, which is a dropdown list (double-click it to display a list of surface types), with the default type of Sphere. The **Y Radius** is the radius of curvature, which is the reciprocal of curvature. Spheres and other rotationally symmetric surface shapes have only a single curvature, and Y is used for this (types such as Y Toroid have X and Y curvatures). You can also choose to display the Y Curvature (reciprocal of radius, e.g., units of 1/mm). See the tip below.

Tip: You can work with radius of curvature or its reciprocal, curvature, by checking or un-checking the **Edit** > **Radius Mode** menu item.

Thickness is defined as the distance to the next surface, measured along the local Z axis of the current surface (which is the optical axis for centered systems such as this). Note that the thickness (air space) of surface 6 is gray and has a small **S** next to it. This thickness is set by a **paraxial image (PIM) solve,** which calculates the thickness at which the paraxial marginal ray has a height of zero at the following surface. This sets the paraxial image distance, where the lens is approximately in focus. This may not be the best focus, however, so the thickness of the image surface is used as a focal shift from the PIM value (the total image distance is the sum of these two values). Optimization usually determines the best focus shift (the combination of PIM solve and variable defocus is recommended for most optical systems).

Glass cells contain the name of the material in the space following the surface, and if it is blank, the material is AIR. The glass determines the index of refraction, which is a fundamental requirement for ray tracing. There are several possible forms for glass names, depending on whether they are from glass makers, defined locally for the lens ("private catalog"), or defined as "fictitious" glass whose index can be varied to allow optimization, as shown in the example (there is a supplied macro, **glassfit.seq**, that can help you convert fictitious glasses into real glasses that you can buy). **Refract mode** determines the basic behavior of a surface, whether rays are refracted or reflected at the surface (double-click the cell to see the choices).

The final column is labeled **Y Semi-Aperture** and represents the size of the optically useful portion of the lens surface. By default, this is a centered, circular aperture calculated by the program to pass the reference rays from all field and zoom positions. You can change this to a user-defined aperture for any surface in several ways, the simplest of which is to right-click and choose one of the **Change to...** options that pops up. You can just accept default apertures for now, though later you will learn about the relationships between apertures, pupil size, and vignetting factors.

Changing and "Committing" Data

Changing data in the LDM spreadsheet is simple—click a non-gray cell and type a new value. You can also double-click a cell to display and edit the full value (or to display a list of choices in some cases). If you change something by mistake, use the **Edit > Undo** menu to fix it (make sure that a spreadsheet or command window is in front; Undo will not be available if a graphics window or dialog box is in front). Note that some cells have a small symbol or "glyph" next to the value, identifying a special state for that cell (e.g., S for solve, V for variable, Z for zoom).

To change the state of any cell (including a gray cell), right-click on it to see a shortcut menu of options (e.g., changing a solve to a variable will remove the solve and allow you to change the value directly, but be sure you want to do this since the solve may be there for a reason).

One of the right-click menu choices on any surface data item will be **Surface Properties**. This opens a large window that gives direct access to ALL properties of that surface, including many that do not appear in the LDM spreadsheet. We will cover Surface Properties a little later.

You can also change data in the LDM spreadsheet by typing appropriate commands at the CODE V> prompt in the Command Window. This requires knowing the applicable command and its syntax (e.g., `THI S5 2.3` will change the thickness of surface 5 to 2.3). When you enter a command this way and press the Enter key, you will also see the corresponding LDM spreadsheet or Surface Properties window update.

Don't Fear Commitment

In CODE V, we use the term "commit changes" to refer to transferring the data from the place it is entered in the user interface (such as a spreadsheet cell or dialog box) to the lens database inside CODE V (sometimes called the "back end" of CODE V). Normally data is committed instantly—that is, as soon as you type or click in another cell, data field, or window. This is similar to other programs such as Excel, except you will also see the corresponding commands displayed in the Command Window.

However, there are some cases in which a command is built from several data values entered in a row of a smaller spreadsheet (e.g., apertures in the Surface Properties window). In this case, the numbers are not committed until the row is completed.

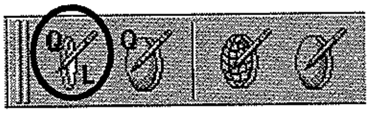
The thing that may be confusing has to do with the different types of windows. Windows in CODE V come in two basic types, those that have **Apply** or **OK** and **Cancel** buttons (these are called dialog boxes), and those that do not (the main examples being the Surface Properties and System Data windows). Dialog boxes with **OK** buttons (including the dialog boxes for CODE V options such as MTF) do not commit anything to the back end until you click OK. If you click Cancel, no changes are actually made. In the case of the Surface Properties and System Data windows (and a few others, all associated with the LDM), you can keep them open while you work in other windows, or close them by clicking the **X** in the upper right-hand corner of the window. Changes made in these windows are committed immediately, just like the LDM spreadsheet; however, you can be sure data is committed to the lens database by clicking the **Commit Changes** button. You can see what data has been committed in the Command Window, which displays the commands generated for these operations.

Don't worry too much about this—you can always use Undo to get back to any earlier state of the lens, in case you change something you did not intend. It's also a good idea to save your lens in a file whenever you make significant changes (**File > Save Lens As** menu).

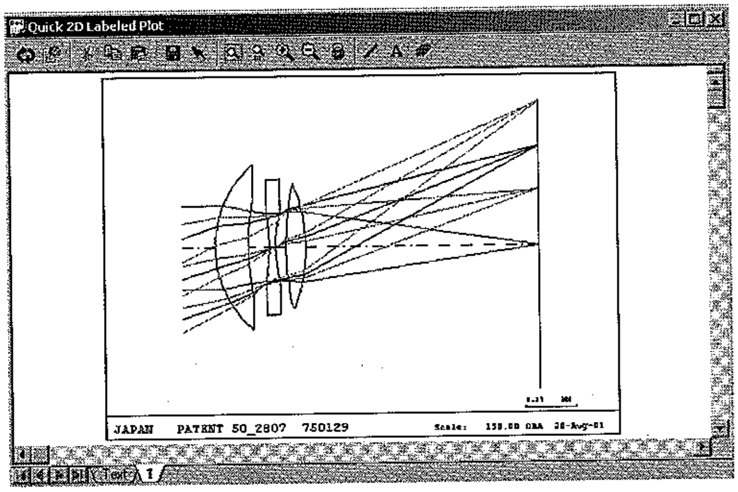
Drawing Pictures

Now you can understand the LDM spreadsheet, but as they say, a picture is worth a thousand numbers. So it's a good idea to draw a picture of the lens as soon as you can. Many problems are easy to spot on a lens picture. There are a number of ways to draw lenses, including the very flexible VIEW option (**Display > View Lens** menu), but for now, there's a quicker way.

- Click the Quick 2D Labeled icon on the toolbar:



It's the middle one that shows a lens and a pencil along with the letter Q (for quick) and the letter L (for labeled—float the mouse over it to see the tool-tip help to see the message "Quick 2D – Labeled"). Keep the resulting window open as you work (resize and move the window as desired). When you change something, click the Execute button in the upper left corner of the window to redraw the lens picture.



Before analyzing this lens, you will more than likely need to scale it to the required effective focal length (EFL).

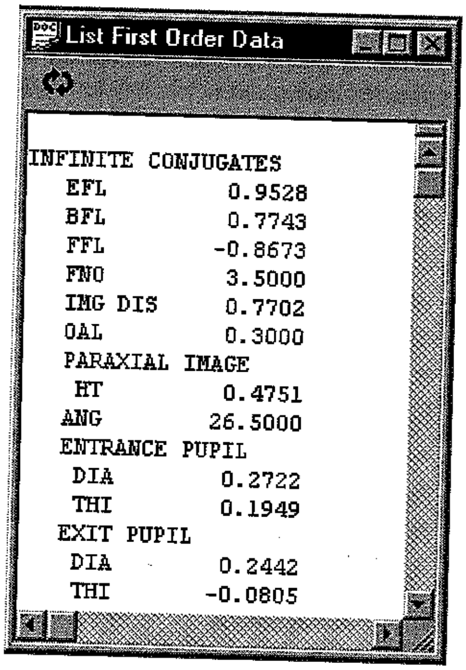
Surface Operations: Scale the Lens

Although you set the f/number and field angles to the desired values in the New Lens Wizard, you need to be sure the lens has the specified effective focal length (EFL) of 6 mm. One way to determine this is to display a window of first order properties.

1. Choose the **Display > List Lens Data > First Order Data** menu, and re-size/re-position the resulting window for convenient viewing.

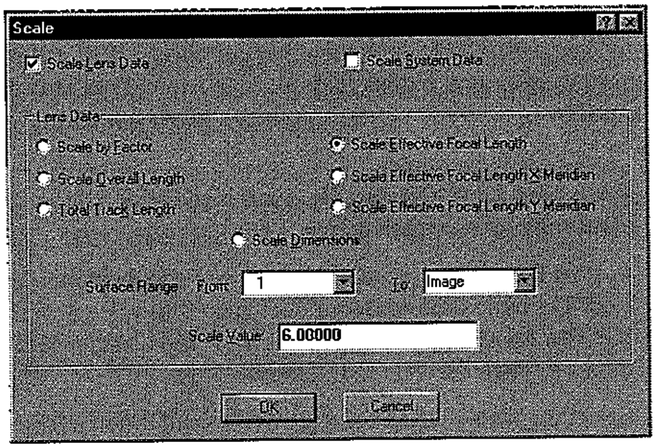
   Note the value labeled EFL in this window (0.9528 mm), which is not optimal for this application. Scaling the lens data is the usual way to fix this.

Tip: You can place the EFL and various other lens properties on the status bar at the bottom of the main CODE V workspace. This allows continuous monitoring of these items. Choose the **Tools** > **Customize** menu and click on the **Status Bar** tab in the **Customize** dialog box to access this feature.



```
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
```

2. Select surfaces 1 to Image in the LDM spreadsheet window (click in the surface # column and drag to Image to select the range).
3. Choose the **Edit** > **Scale** menu to display a dialog box (note that the surface range is set to 1 to Image).
4. Click the button labeled **Scale Effective Focal Length**, then enter the value **6.0** in the field labeled **Scale Value.**



☑ Scale Lens Data

☐ Scale System Data

○ Scale by Factor

○ Scale Overall Length

○ Total Track Length

● Scale Effective Focal Length

○ Scale Effective Focal Length X Meridian

○ Scale Effective Focal Length Y Meridian

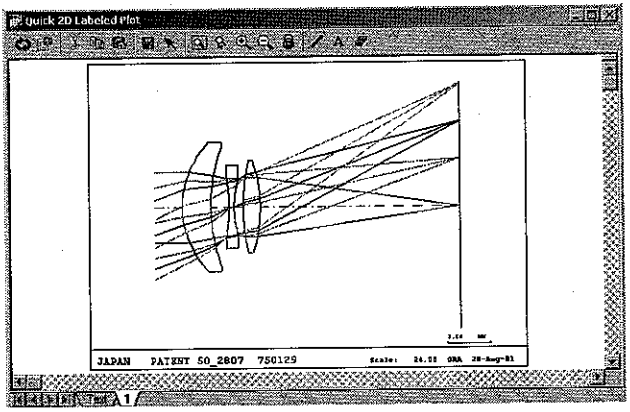
○ Scale Dimensions

Surface Range From: 1 To: Image

Scale Value: 6.00000

5. Click **OK** to scale the lens.
6. Click the Execute button in the **List First Order Data** window to update it.

   Note that the EFL value is now 6 mm as desired. Note also that the paraxial image height is 2.99 mm (close enough to the desired 3 mm).
7. Click the Execute button in the **Quick 2D Labeled Plot** window to update the picture as shown below.



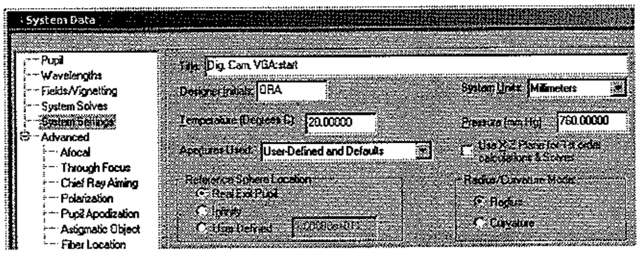
New Title and Starting "Save Lens"

So far, so good, but before continuing, you should label and preserve the work you have done up to now. Noting that this is an expired patent which is about to be changed by optimization, you can set a new lens title and save this as a starting point.

- Choose the **Lens > System Data** menu and click **System Settings** in the System Data window's navigation tree.

  System Data is where most non-surface-related data can be viewed and modified. The basic System Data values (pupil, wavelengths, field) were defined in the New Lens Wizard, but you can view and change these properties and many others through the System Data dialog box.

- Select the **Title** field and change it to something like **Dig. Cam. VGA: start** (you have up to 80 characters, but don't include any quotes or apostrophes). Tab to or click in another field to commit this data to the CODE V lens database.



Title: Dig. Cam. VGA:start

Designer Initials: ORA

System Units: Millimeters

Temperature (Degrees C): 20.00000

Pressure (mm Hg): 760.00000

Apertures Used: User-Defined and Defaults

☐ Use X-Z Plane for 1st order calculations & Solves

Reference Sphere Location:
● Real Exit Pupil
○ Infinity
○ User Defined

Radius/Curvature Mode:
● Radius
○ Curvature

- Choose the **File > Save Lens As** menu and enter a file name such as **DigCamStart.len**, then click **Save**.

Analyze the Starting Point

There are many types of analysis in CODE V, but only a few of them are needed to determine if you are meeting the specs. The results of these analyses will also guide the setup for optimization (if required):

- First order requirements (done after scaling the lens, as detailed in "Surface Operations: Scale the Lens" on page 29; the scaled lens has the correct first-order focal length and image height)
- Distortion (Field Curves and/or Distortion Grid)
- Sharpness (diffraction MTF—this will also establish depth of focus, by analyzing MTF with a different object distance)
- Vignetting/illumination (Transmission Analysis)

In addition, you will also use a couple of quick analysis features for reference (spot diagram and ray aberration curves). We will explain the basics of these analysis options now. Additional information will be provided in a later section of this guide that covers evaluation features. There is one more thing that needs to be done with the starting point, though it does not neatly fit into any specific analysis category: establish feasibility.

Assuming that someone will eventually manufacture this lens, there are certain practical issues. Are the elements too small or too large to make easily? Are they too thin or too thick for practical fabrication? Can they be assembled and mounted easily? Is the glass available, and is it expensive? These are some basic questions, which must be answered on the basis of looking at the basic lens data and comparing it to some known experience (you may have to do some calculations and perhaps ask someone who has designed or built similar optics).

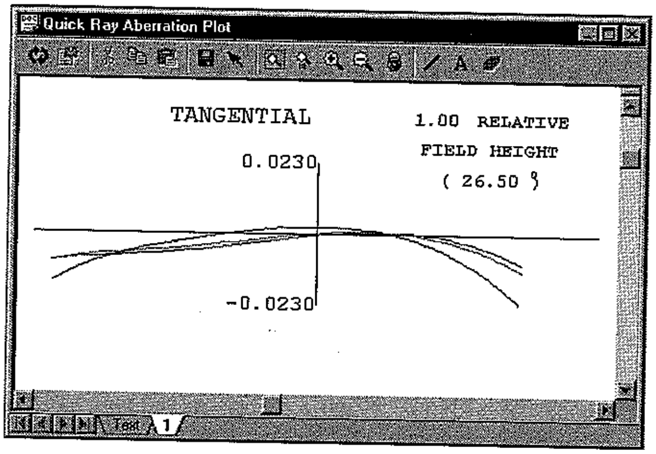
There are other feasibility issues that are more technically complex. One is tolerance analysis, which will be introduced later in this guide. This relates to how accurately the elements must be fabricated and mounted to maintain a required level of performance. Another that won't be covered is thermal analysis (although CODE V can help with some aspects of this, such as changes in performance due to a simple temperature change).

Quick Ray Aberration Curve

A ray aberration curve is a useful way of looking at ray trace data to see patterns that may cause problems. Transverse ray aberrations are measured on the image surface as the distance from a particular ray to the chief ray for the same field point (for a perfect lens, this should be zero for every ray traced from the same field point). This is plotted as a function of position in the stop or pupil for a line of evenly spaced rays (a ray fan).

You are first looking for large deviations, including separations between the curves for different wavelengths (chromatic aberration). You may also look for distinctive patterns that represent coma, astigmatism, and other basic aberrations. Experience can tell you where such aberrations come from, suggesting where you might make corrections, perhaps in the form of additional elements or aspheres.

The Quick Ray Aberration plot is a one-click version, which you run by clicking the Quick Ray Aberration plot toolbar button, shown below (for the general case, choose the **Analysis** > **Diagnostics** > **Ray Aberration Curves** menu, option name: RIM, for "rim ray"). The Quick version is actually done by a macro and performs automatic scaling (it also supplies a text table of ray aberrations, generated by the ANA option). Note that the following graph is shown after zooming and positioning only the highest field angle in the Quick Ray Aberration Plot window.



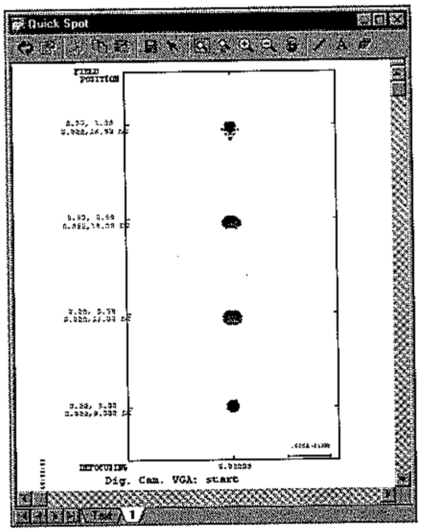
The starting point doesn't show signs of any gross aberrations, though you can only tell this by looking at the scale and knowing what is big. The automatic scale value here is 0.023 mm, 23 microns. For comparison, the Airy disk diameter (diffraction spot size for a perfect lens) is 2.44*(wavelength)*(f/number), or about 0.004 mm for f/3.5. This lens is not diffraction limited (nor would you expect it to be), but its aberrations are within a factor of 6 of the Airy size.

Tip: Always use the graphical zoom tool to zoom in on the scale numbers for plots. Automatic scaling may make a lens look good, but the scale size may be large.

Quick Spot Diagram

A spot diagram is not a required part of the spec, but it is a quick and easy analysis that gives you a graphical picture of the imaging quality of the lens. Basically, many rays from each field point are traced through the system, forming a rectangular grid in the entrance pupil. A scatter plot of the rays' position is done on the image surface, one for each field, and usually color coded for wavelength, giving an idea of chromatic aberration. The scale for plotting is determined automatically to fit the spots in the plotting area, so as with any analysis plot, you must check the scale size.

To run this, click the Quick Spot Diagram button (general case: **Analysis > Geometrical > Spot Diagram,** option name SPOT). For this lens, the spots for all fields are roughly the same size, though the shapes are different. The scale bar is 0.050 mm, 50 microns.

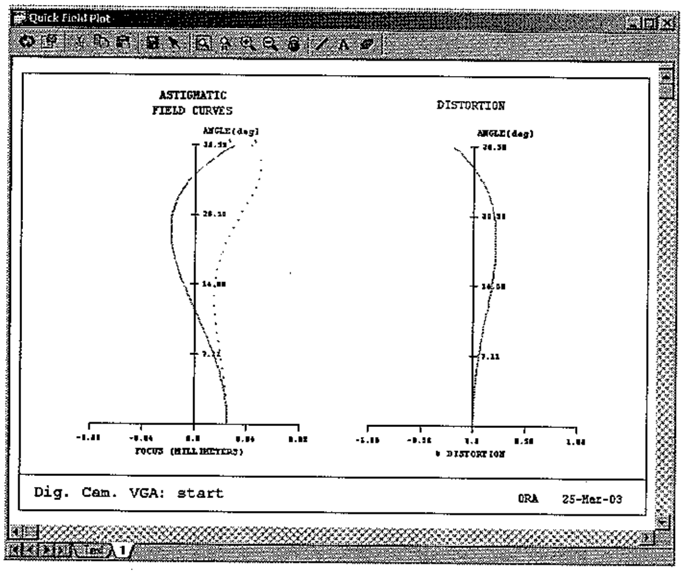


Tip: The supplied macro **spotdet.seq** will plot spot diagrams with superimposed circles or rectangles representing a specified detector size or Airy disk. Choose the **Tools > Macro Manager** menu and locate the macro under **Sample Macros/ Geometrical Analysis.** Note that you will have to fill in the required data to run this macro.

Distortion

The paraxial image height is related to field angle by the relationship $h = f \tan \theta$. If the real image height differs from this paraxial prediction, you have distortion. Distortion is therefore a field-related aberration, and it is often displayed as a plot along with another field-based aberration, astigmatism. These field curves are available by choosing the **Analysis > Diagnostics > Field Curves** menu, or by clicking the Quick Field Plot button on the toolbar.

The resulting distortion curve has field angle as the vertical coordinate and percent distortion as the horizontal coordinate. It shows that the starting point is well within the specified 4% distortion for the lens. In fact, it's less than plus or minus 1% across the entire field of view. Astigmatism (left side in plot window below) is well corrected at the full field, but there is substantial zonal residual at the intermediate fields.

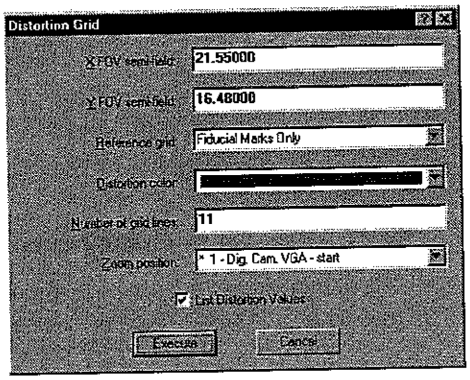


Dig. Cam. VGA: start

ORA 25-Mar-03

A distortion grid is another way to view distortion that is perhaps a little more intuitive. In this case, you see a rectangular grid that represents the ideal (paraxial) image, with the distorted grid superimposed on it. Since the field of view is defined by field angle for this lens, you need to convert the CCD horizontal (X) and vertical (Y) dimensions into field angle using $h = f \tan \theta$ again (we used the 3 mm corner distance to define the maximum field, but in this case we want to view the actual format of the field). From the spec, recall that the full detector dimensions are 3.55 x 4.74 mm. Divide these by twice the focal length and take the arctan to get the maximum Y and X field angles (16.48° and 21.55°).

1. Choose **Analysis > Diagnostics > Distortion Grid** menu.
2. Enter **21.55** in **X FOV semi-field** and **16.48** in **Y FOV semi-field**. Also choose **Fiducial Marks Only** for the reference grid, and click **Execute**.



Distortion Grid

X FOV semi-field: 21.55000

Y FOV semi-field: 16.48000

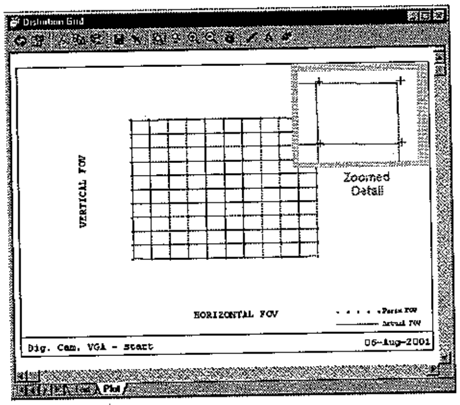
Reference grid: Fiducial Marks Only

Distortion color:

Number of grid lines: 11

Zoom position: * 1 - Dig. Cam. VGA - start

☑ List Distortion Values



The distortion is small, so you need to zoom in on the plot to see it. Fiducial marks show the paraxial ray positions. This makes a less cluttered plot for small distortion cases.

MTF ("Sharpness")

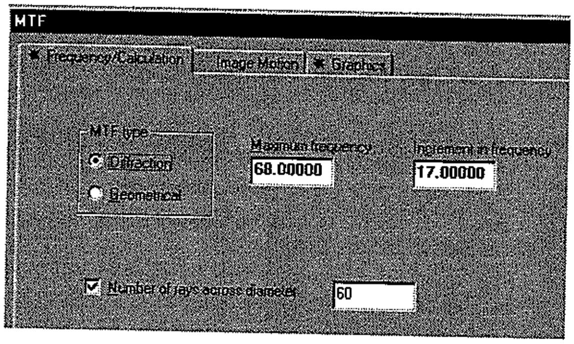
With any type of camera, users are interested in qualities such as sharpness or resolution. Optical designers relate these qualities to MTF, or modulation transfer function. Modulation is essentially relative contrast, with 1.0 representing ideal contrast (perfect black and white, no degradation to intermediate grays). For large features (low spatial frequency), even a poor lens will have good contrast, while for higher frequencies (fine details), aberrations and diffraction blend the dark and light areas. If you determine and plot the MTF for the full range of spatial frequencies, for all field points, you can define the sharpness of a lens in very compact form.

1. Choose the **Analysis > Diffraction > MTF** menu.

   Note that there is a Quick MTF button, but we want specific spatial frequencies, and the quick version doesn't support this.

2. On the **Frequency/Calculation** tab, enter **68** for the **Maximum frequency** and **17** for the **Increment in frequency**.

   Note that when you change a value on a tab, a red star (also called a change indicator), displays next to the tab title.



MTF type: ● Diffraction ○ Geometrical

Maximum frequency: 68.00000

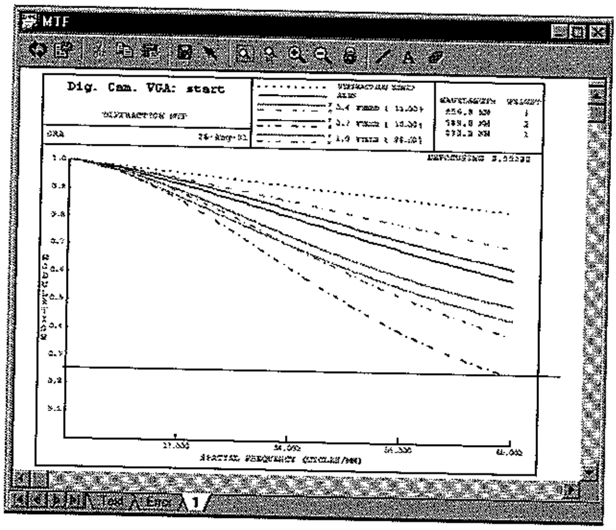
Increment in frequency: 17.00000

☑ Number of rays across diameter: 60

3. On the **Graphics** tab, enter **68** for the **Maximum plot frequency** and click **OK**.

   Recall that the CCD array has a maximum spatial frequency of about 67 lines/mm, and the combination of 17 and 68 (4*17) works well for this analysis.

Tip: You can use the line-drawing and text tools on any graphics window to add information to help you read and interpret the plot. The added graphics will go away if you recalculate the plot, but you can choose the **File > Save Window As** menu if you want to save the annotated plot.



It appears that the starting lens has very good MTF properties, meeting the low and high frequency sharpness requirements for all fields and azimuths (MTF can vary with direction, so two orthogonal directions are calculated, radial and tangential). The horizontal line at 0.25 MTF was added by hand using the line drawing tool.

Note that we have not yet considered the depth of field issue, which requires that the lens meet the MTF spec with the object distance at 750 mm as well as the current "infinite" (1.0E10 mm) value. We will discuss this in Chapter 3, which covers optimization.

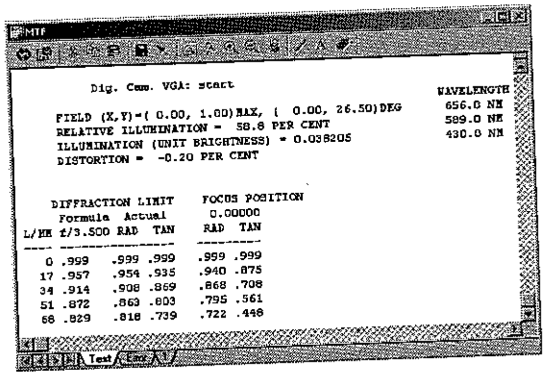
Vignetting/Illumination

The spec requires at least 60% relative illumination at the corner of the field (full field in your system data). This is to include vignetting effects (clipping of off-axis rays due to apertures on surfaces other than the aperture stop surface) as well as angular effects ("cosine fourth" is a well-known approximation to relative illumination vs. angle). The program will model the relationship between pupil size (or f/number), surface apertures, and so-called vignetting factors.

The system used for this is very flexible but a bit complex and will be explained in more detail in Chapter 10. Here is the short version: Vignetting factors determine the reference rays, which in turn determine default apertures. These in turn determine the rays that get through in calculations such as MTF and many others. For design purposes, you can directly change the vignetting factors, to expand or contract the cone of light from off-axis fields, and the default apertures are adjusted accordingly. In this patent, the upper and lower Y vignetting factors for the full field are 0.21 and 0.11, respectively. What relative illumination does this produce?

There are at least two ways to look at this, and one is already done.

- Click the **Text** tab of the MTF output window you created in the last section. Scroll down to the output table for the last field. (0.0, 26.5 degrees).



```
        Dig. Cam. VGA: start                                      WAVELENGTH
                                                                   656.0 NM
   FIELD (X,Y)=( 0.00, 1.00)MAX, (  0.00, 26.50)DEG               589.0 NM
   RELATIVE ILLUMINATION =  58.8 PER CENT                          430.0 NM
   ILLUMINATION (UNIT BRIGHTNESS) = 0.038205
   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
  17 .957   .954 .935   .940 .875
  34 .914   .908 .869   .868 .708
  51 .872   .863 .803   .795 .561
  68 .829   .818 .739   .722 .448
```

Note that in addition to the tabular MTF data, there is additional information for each field point. Relative illumination is especially helpful in this case, and it is 58.8%, just a little below the required 60% in the spec (note that the value for cos**4 of 26.5° is 0.64). You could play with the vignetting factors (found on the

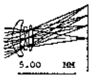
Fields/Vignetting page of the **System Data** window) to try to improve this, but since this is close to the spec, you can leave the vignetting alone for now, and see if it improves during optimization.

The other place to see illumination data is in the **Transmission Analysis** option (**Analysis** > **System** menu), which will provide more detailed illumination data, including the effects of coatings, if any. For this option, CODE V will assume a quarter-wave anti-reflection coating on each glass surface, unless you delete this coating or apply a user-defined coating.

Establish Feasibility

This lens looks pretty good as it is, considering that you simply picked an old patent based on some requirements, then scaled it. Are you done? Consider the size and thickness of the elements. Although it is possible to fabricate and mount very small lens elements, these elements are awfully thin for their size.

The original patent had a focal length of about 1 mm, though it was probably scaled to unit focal length for patent purposes (it may have been a much larger lens, perhaps for 35 mm film, for which it would have a focal length of about 43 mm for this field of view). At EFL=6 mm, the middle (negative) element is 1.5 mm in diameter and only 0.126 mm thick -- just 126 microns (at 43 mm, this element is a more reasonable 0.9 mm thick). Just to give you a visual impression, here is a plot of this lens at approximately real scale:



For optics of this size to be handled and worked, you will need to require reasonable center and edge thickness values, perhaps 0.9 mm for the center and 0.8 mm for the edge thickness values. This means that as good as this design appears to be, you are not done yet. You will need to use constrained optimization (the Automatic Design or AUTO option) to reconfigure the lens to meet all the requirements.

There is at least one additional issue of practicality, which is glass selection. All three fictitious glasses in the patent are all high index glasses (1.786, 1.717, 1.835). High or low index (e.g., >1.65 or <1.45) glasses are generally less common and thus more expensive than mid-range index glasses. You can use the glassfit.seq macro to quickly convert these glasses to the closest real equivalents (choose the **Tools > Macro Manager** menu, then run **glassfit.seq**, found under **Sample Macros/Material Information** in the **Macro** dialog box). This macro runs interactively in the Command Window (question/answer format). Using Schott glass and allowing automatic replacement, you get the following:

```
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
```

Note that only SF1 is a "preferred" (common) glass, while NLASF41 is an "inquiry" glass (special order). LAFN28 is listed as US $315 per pound ($693/kg), which is about 19 times the price of BK7, the most common optical glass. These are not the best choices for a low-cost digital camera, even if the elements are very small (note that you could use the COST option to find the weight and estimated glass cost; choose the **Analysis > Fabrication Support >Cost Analysis** menu). It certainly would make sense to try to constrain the glass choice to a lower-index and cheaper region of the glass map. This can be done in AUTO.

Conclusions

To summarize, in this chapter you have:

- Interpreted a spec for a digital camera lens design
- Used the New Lens Wizard to locate a suitable starting point from a database of expired patents
- Scaled the lens for the application
- Analyzed the starting point and determined some guidelines for optimization

If you haven't saved your work, you should do so now, so it is available for use in subsequent chapters of this guide. Choose the **File > Save Lens As** menu and give the lens file a name such as **DigCamStart.len**. In the next chapter, you will use this starting point to optimize a lens that has acceptable optical performance as well as reasonable fabrication possibilities.