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Apertures and Vignetting 101

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If you're a student picking up optical design software for the first time (or even the hundredth time!), one common challenge you might face is understanding how the software handles apertures and vignetting in a lens system. This article discusses these concepts within CODE V®.

What Are Apertures & Vignetting?

Apertures (strictly speaking, "clear apertures") are fairly easy to understand. Clear apertures are simply the opening associated with each surface that light can pass through. Light inside the clear aperture proceeds to the next surface, light outside the clear aperture is blocked. In all standard imaging optical systems, there is one clear aperture that is special, and is typically the only aperture to limit how much light gets through the optical system for the on-axis field. This surface is defined as the "Aperture Stop," or simply the "Stop." For some systems, it is the only aperture that limits the light bundle for off-axis fields as well.

In many systems, however, off-axis light will be blocked by other clear apertures than just the Stop. Consider Figure 1. The Stop is the only clear aperture that clips the "on-axis" ray bundle (shown in black). However, for the off-axis ray bundle, some of the rays at the bottom that would have passed through the Aperture Stop are blocked by the clear aperture on the front surface of the first lens, and some of the rays at the top that pass through the Aperture Stop are blocked by the clear aperture on the rear surface of the third lens. Only the ray bundle represented by the blue rays reach the image plane; all the red rays are blocked.
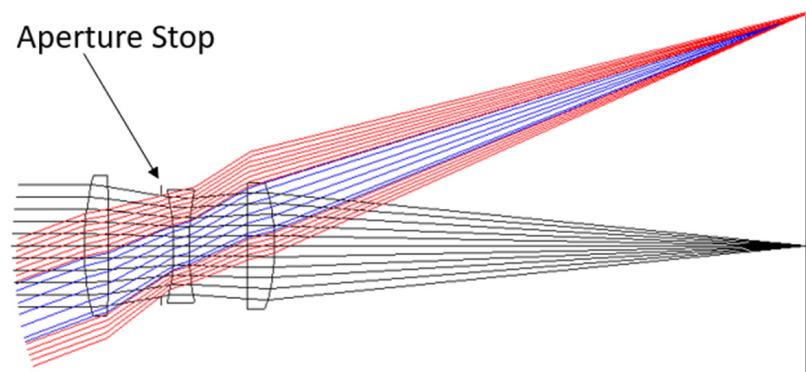

Figure 1: Lens with off-axis vignetting

This blocking of rays by clear apertures on surfaces other than the Aperture Stop is called vignetting. Sometimes vignetting is undesired, since less light reaches the image (sensor location). Often, it is deliberately used to improve the off-axis performance of a lens by blocking aberrated rays or to reduce the diameter of the overall lens system.

In CODE V, every field point has four "vignetting factors" associated with it (**Lens > System Data** menu, **Fields/Vignetting** page; +Y or VUY; -Y or VLY; +X or VUX; and -X or VLX). Figure 2 shows the Fields/Vignetting window in CODE V that includes the vignetting factor table.
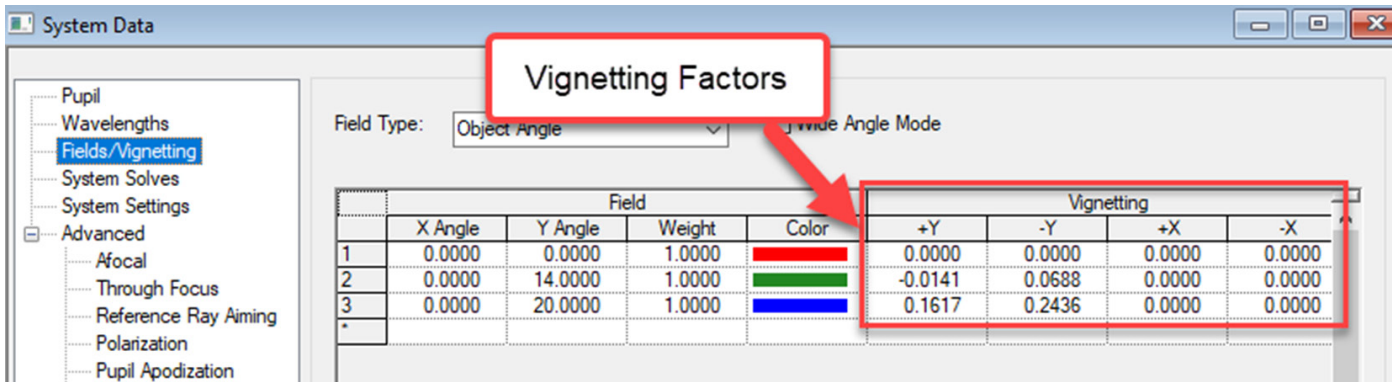

Figure 2: Fields/Vignetting window in CODE V

These factors, along with the pupil definition (**Lens > System Data** menu, **Pupil** page) define the limits of ray bundles that enter the optical system. It is important to understand that these "vignetting factors" are not only used to model ray clipping by clear apertures, but they are also used to model "Pupil aberration."

In CODE V, the vignetting factors are applied at a special location called the Entrance Pupil (which is where the Aperture Stop appears to be when you look at Aperture Stop through any lenses that are in front of it). Since the lenses can cause aberrations, a ray bundle definition with no vignetting on the Entrance Pupil may not fully fill the actual Aperture Stop (or, may overfill it). In CODE V, the vignetting factors adjust the ray bundles at the Entrance Pupil to account for both clipping by clear apertures and pupil aberrations, if the Aperture Stop is defined somewhere within the optical system. Figure 3 shows the changing appearance of the Entrance Pupil for a fisheye lens.

Figure 3: Changing appearance of the entrance pupil for a fisheye lens

When entering lens prescription information into CODE V, sometimes you know the clear apertures, but often you only know (or can estimate) the off-axis vignetting. Having limited information about clear apertures and/or vignetting factors is particularly common in patent lens documents. Whatever information you have, or can infer, CODE V has tools to set the vignetting factors based on the clear apertures, or conversely, to set the clear apertures based on vignetting. It is important to keep the vignetting factors and clear aperture specifications consistent. Most analysis features use the clear apertures to limit the ray bundles (but use the vignetting factors to determine reasonable default clear apertures). Other CODE V features, most notably optimization, use the pupil and vignetting factors to define the incoming ray bundles. This is a useful default, since the clear aperture needed to maintain a particular pupil specification and vignetting can change as the system optimizes.

Patent Lens Example

To illustrate these concepts, we'll use a lens from the CODE V Patent Lens database. US 1,987,878 (or02448) is an f/4.5 triplet with a 28-degree semi-field of view. The Effective Focal Length (EFL) is unity (typical for patents), but can be easily scaled to 50 mm. The patent document does not include clear aperture or vignetting information. It only defines the pupil at f/4.5, and indicates the Aperture Stop surface location.

When you load this patent lens from the CODE V database, you will see that there is non-zero vignetting information defined for the off-axis fields (Figure 4). Where do these values come from?

| | Field | | | | Vignetting | | | |
	X Angle	Y Angle	Weight	Color	+Y	-Y	+X	-X
1	0.0000	0.0000	1.0000	(red)	0.0000	0.0000	0.0000	0.0000
2	0.0000	20.0000	1.0000	(green)	0.0000	0.2000	0.0000	0.0000
3	0.0000	28.0000	1.0000	(blue)	0.2000	0.5000	0.0000	0.0000
*								

Figure 4: Vignetting information for Patent Lens or02448

The answer is that the values are an estimate of how much off-axis vignetting is needed to reduce the aberrations and have reasonable edge thicknesses on the lenses. It is often up to the optical designer to make this determination.

Figure 5 shows the lens layout, transverse ray aberration curves, and spot sizes for the original patent lens prescription with the vignetting factors set to zero at all fields.
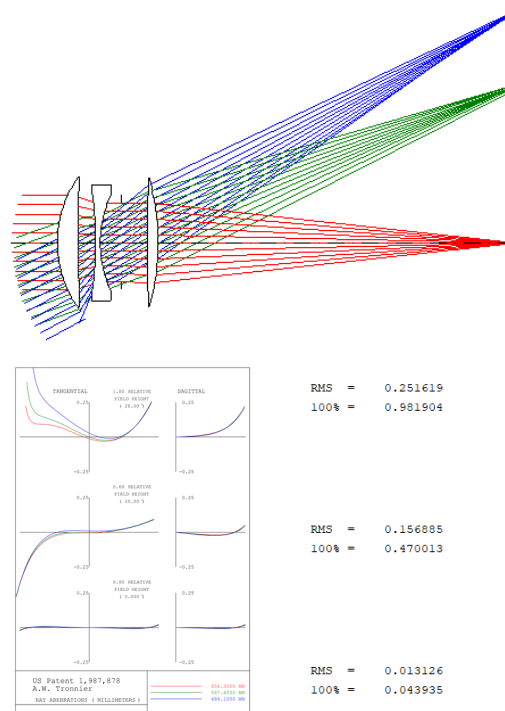

Figure 5: Patent lens with vignetting set to zero at all fields

You can see that the front lens is too thin to be large enough to allow all of the off-axis ray bundles to pass. From the transverse ray aberration curve, you can also see that the -Y side of the pupil has significant aberrations for the two off-axis fields. Further, if you zoom in on the area of the Aperture Stop (Figure 6), you can see that with vignetting factors set to zero, the off-axis rays do not fill the stop for the third field, and rays at the bottom of the pupil extend a bit beyond the stop for the second field. In CODE V, by definition, the zero vignetting factors indicate that the paraxial entrance pupil is being exactly filled, so the underfilling/overfilling of the Stop is an indication that this system has pupil aberration.
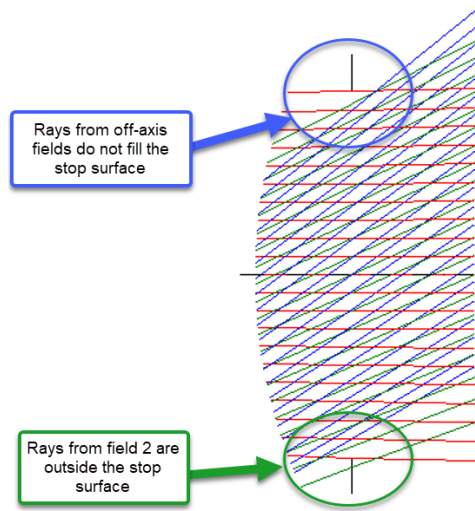
Figure 6: Unvignetted off-axis bundles illustrating pupil aberration at the Aperture Stop

If we re-apply the vignetting factors shown in Figure 4 that were estimated for this design, we can see in Figure 7 below that the off-axis rays no longer extend beyond the edge of the first lens, the most significantly aberrated portions of the off-axis ray fans are eliminated/reduced, and the RMS and 100% spot sizes are reduced considerably. There is no change to the on-axis performance, since there is no vignetting on-axis.
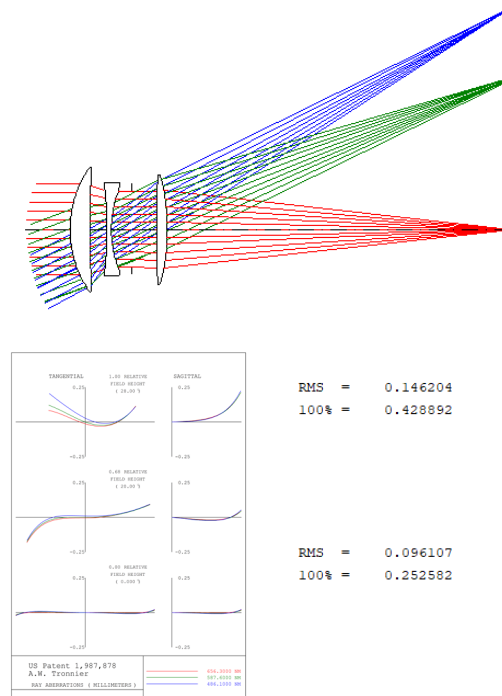

Figure 7: Patent lens with estimated vignetting

CODE V automatically computes implicit (default) clear apertures based on the pupil and vignetting factors. These are displayed on a gray background (with a circle-glyph) in the Y Semi-Aperture column of the Lens Data Manager (LDM) spreadsheet (Figure 8).

Figure 8: Default clear aperture values in Lens Data Manager

If the lens is optimized, these default clear apertures will likely change, but they will remain consistent with the pupil specification and vignetting factors. That is the benefit of CODE V's default behavior of using vignetting factors to control the bundle size during optimization, before the final, required clear apertures sizes are known.

It is important to understand that the approximated vignetting factors may not be exactly realizable based on the computed default apertures for this lens, especially when multiple off-axis fields are involved. If we look at Figure 7, it is clear that the vignetting due to aperture clipping is caused by the apertures on Surface 1 and Surface 7 in the lens prescription. In Figure 9, we can convert those to explicit, centered, circular clear apertures by right-clicking the Semi-Aperture cell, choosing **Change to Circular Aperture** and then choosing the **Lens > Calculate > Set Vignetting Data** menu to reset the vignetting factors to make them consistent with these two explicit clear apertures (and the Stop clear aperture whose default size is always based on Field 1 ray bundle).

	Field				Vignetting			
	X Angle	Y Angle	Weight	Color	+Y	-Y	+X	-X
1	0.0000	0.0000	1.0000		0.0000	0.0000	0.0000	0.0000
2	0.0000	20.0000	1.0000		-0.0016	0.2000	-0.0023	-0.0023
3	0.0000	28.0000	1.0000		0.2000	0.4788	-0.0065	-0.0065

Surface #	Y Semi-Aperture
Object	
1	6.8698
2	6.6183
3	5.1262
4	4.6582
Stop	4.5703
6	5.8670
7	6.0010
Image	26.8273

Figure 9: Patent lens with actual vignetting factors based on explicit clear apertures

You can see that the actual vignetting based on real apertures defined on Surfaces 1 and 7 is a good match to the approximated vignetting factors for the patent. However, the actual values are (slightly) different. Also, the small negative vignetting factors are

another indicator that there is some pupil aberration in this lens. For a system with no pupil aberration, and an Aperture Stop that just passes the on-axis ray bundle, the off-axis vignetting factors will be either zero or positive.

Defining the Clear Apertures for Fabrication

Finally, let's assume we are ready to have the optical system built. Since fabricators prefer rounded parameters when possible (to make measurement easier), let's round the clear aperture values for all surfaces. We can quickly convert all of the default apertures to explicit, centered clear apertures using the **Lens > Calculate > Set Apertures** menu (and then select the checkbox to convert the default apertures).
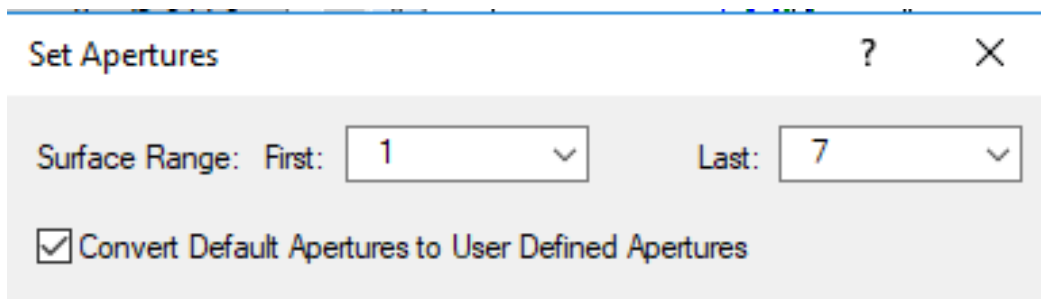

Figure 10: Converting default apertures to centered clear apertures

We then enter explicit apertures values with one or two digits of precision. Since we reduced the Stop radius by 0.3 microns, but don't want any on-axis vignetting, we can redefine the entrance pupil diameter by choosing the **Lens > Calculate > Set Pupil Specification** menu (which also increases the f/# by an insignificant amount). Choosing the **Lens > Calculate > Set Vignetting Data** menu again resets the vignetting factors to make them consistent with these larger, rounded clear apertures, as shown in Figure 11. You should then re-evaluate the performance to make sure everything is working as expected!

Surface #	Y Semi-Aperture
Object	
1	7.0000
2	7.0000
3	5.1000
4	5.1000
Stop	4.5700
6	6.0000
7	6.0000
Image	26.8273

	Field				Vignetting			
	X Angle	Y Angle	Weight	Color	+Y	-Y	+X	-X
1	0.0000	0.0000	1.0000		0.0000	0.0000	0.0000	0.0000
2	0.0000	20.0000	1.0000		-0.0014	0.1877	-0.0023	-0.0023
3	0.0000	28.0000	1.0000		0.2002	0.4472	-0.0012	-0.0012
*								

Figure 11: Patent lens with actual vignetting factors based on explicit, rounded clear apertures

Summary and Final Comments

The three main takeaways from Apertures & Vignetting 101:

1. While apertures and vignetting may seem confusing, the approach used in CODE V is both logical and flexible. It allows you to enter the information you know, and compute the information that you may need.

2. Vignetting factors in CODE V model clipping of the ray bundles by clear apertures and account for pupil aberrations between the Entrance Pupil and the Aperture Stop.

3. Keep the Clear Aperture values and Vignetting factor values consistent! There are many tools in the **Lens > Calculate** menu to achieve this (as well as equivalent commands).

A final thing to remember is that virtually all of the analyses in the **Analysis > Geometrical** and **Analysis > Diffraction** menus (e.g., spot diagrams, MTF, PSF, etc.) use clear aperture information to limit the ray bundles. By default, these clear apertures are computed from the pupil and vignetting factors – but they can always be defined explicitly. Optimization, the Lens View, and the Diagnostic analyses, by default, determine the ray bundles from the pupil and vignetting factors. However, there are ways to tell CODE V to use the aperture information instead, when that is important for your work.

We hope this article helps to demystify aperture and vignetting in CODE V.

Author Bios

Julie Bentley, PhD

Julie Bentley received her BS, MS, and PhD degree in optics from the Institute of Optics, University of Rochester. Her PhD thesis focused on the integration of the design and manufacture of gradient-index optical systems. After graduating, Bentley spent two years at Hughes Aircraft Co. in California designing optical systems for the defense industry and twelve years at Corning Tropel Corporation in Fairport, New York, designing and manufacturing precision optical assemblies such as micro lithographic inspection systems. She has been teaching optical design courses at the University of Rochester since 1998. Her main teaching interests include geometrical optics, optical design, and tolerancing. She also runs an optical design consulting company – Bentley Optical Design.

Bentley is a fellow of both SPIE and OSA and has served as the president of the local OSA chapter and a three year term on the SPIE Board of Directors. She is the co-author of the SPIE Field Guide to Lens Design (2012), a book that provides physicists, engineers, and scientists a reference for deciphering the nuances of lens design. She also recently published her second book on optical design Designing Optics with CODE V (2018) which gives beginner design students a hands-on approach to learning optical design with software examples.

David Hasenauer

David M. Hasenauer is the CODE V Product Manager in the Optical Solutions Group at Synopsys, Inc. (formerly Optical Research Associates, ORA®). He joined Optical Research Associates in 1990 and was a member of the Engineering Services Group for nine years, where he performed optical design and analysis for systems in a wide range of application areas. As the CODE V Product Manager, he is responsible for product direction and planning, as well as the creation of technical marketing materials.

Hasenauer received his BS in Optics from the University of Rochester (New York). Prior to joining ORA/Synopsys, he worked for Texas Instruments, Inc. in Dallas, Texas. He was a member of the Group Technical Staff, and also Supervisor of TI's Optical Design Group.

Hasenauer holds six U.S. patents and is author or co-author of seven publications in the field of optical design/engineering. He is a Senior Member of both the SPIE and OSA.