

Field Guide to **Lens Design**

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Field Guide to Lens Design

Optical design has a long and storied history, from the magnifiers of antiquity, to the telescopes of Galileo and Newton at the onset of modern science, to the ubiquity of modern advanced optics. The process for designing lenses is often considered both an art and a science. While advancements in the field over the past two centuries have done much to transform it from the former category to the latter, much of the lens design process remains encapsulated in the experience and knowledge of industry veterans. This *Field Guide* provides a working reference for practicing physicists, engineers, and scientists for deciphering the nuances of basic lens design. Because the optical design process is historically (and quite practically) closely related to ray optics, this book is intended as a companion to the *Field Guide to Geometrical Optics*, in which first-order optics, thin lenses, and basic optical systems are treated in more detail. Note that this compact reference is not a substitute for a comprehensive technical library or the experience gained by sitting down and designing lenses.

This material was developed over the course of several years for undergraduate and graduate lens design classes taught at the University of Rochester. It begins with an outline of the general lens design process before delving into aberrations, basic lens design forms, and optimization. An entire section is devoted to techniques for improving lens performance. Sections on tolerancing, stray light, and optical systems are followed by an appendix covering related topics such as optical materials, nonimaging concepts, designing for sampled imaging, and ray tracing fundamentals, among others.

Thanks to both of our families—Danielle, Alison, Ben, Sarah, Julia, and especially our spouses, Jon and Kelly. The cats will now get fed, and all soccer parents beware!

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L-3 Communications

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Glossary of Symbols and Acronyms

A	Area
AOI	Angle of incidence
AR	Antireflection
BBAR	Broadband antireflection coating
BFL	Back focal length
BFS	Best fit sphere
BRDF	Bidirectional reflectance distribution function
BSDF	Bidirectional scattering distribution function
BTDF	Bidirectional transmittance distribution function
c	Surface curvature
C	Lens conjugate factor
CA	Clear aperture
CCD	Charge-coupled device
CDF	Cumulative distribution function
CGH	Computer-generated hologram
CMOS	Complementary metal-oxide semiconductor
CRA	Chief ray angle
CT	Center thickness
CTE	Coefficient of thermal expansion
CTF	Contrast transfer function
d	Airspace
d	Thickness
DLS	Damped least squares
dn/dT	Thermo-optic coefficient
DOE	Diffractive optical element
EFL	Effective focal length
EPD	Entrance pupil diameter
ESF	Edge-spread function
ETD	Edge thickness difference
f	Focal length
$f/\#$	f -number or relative aperture
FEA	Finite-element analysis

Glossary of Symbols and Acronyms

FFL	Front focal length
FFOV	Full field of view
FFT	Fast Fourier transform
FOV	Field of view
GQ	Gaussian quadrature
GRIN	Gradient index
h, h'	Object/image height
H	Lagrange invariant
H	Normalized field coordinate
HFOV	Half field of view
HO	Higher order
HOE	Holographic optical element
HR	High-reflection
i, i'	Angle of incidence w.r.t. surface normal
i, i_a	Marginal ray angle w.r.t. surface normal
$\bar{i}, i_b$	Chief ray angle w.r.t. surface normal
ID	Inner diameter of a lens barrel or mount
IR	Infrared
L	Radiance
LOS	Line of sight
LR	Limiting resolution
LSF	Line spread function
LWIR	Long-wave infrared
m	Diffraction order
m	Magnification
MP	Magnifying power (magnifier or telescope)
MTF	Modulation transfer function
MWIR	Midwave infrared
n, n'	Index of refraction
$n(z), n(r)$	Gradient index profile function
NA	Numerical aperture
NITD	Narcissus-induced temperature difference
NRT	Nonsequential ray tracing
NUC	Nonuniformity correction

Glossary of Symbols and Acronyms

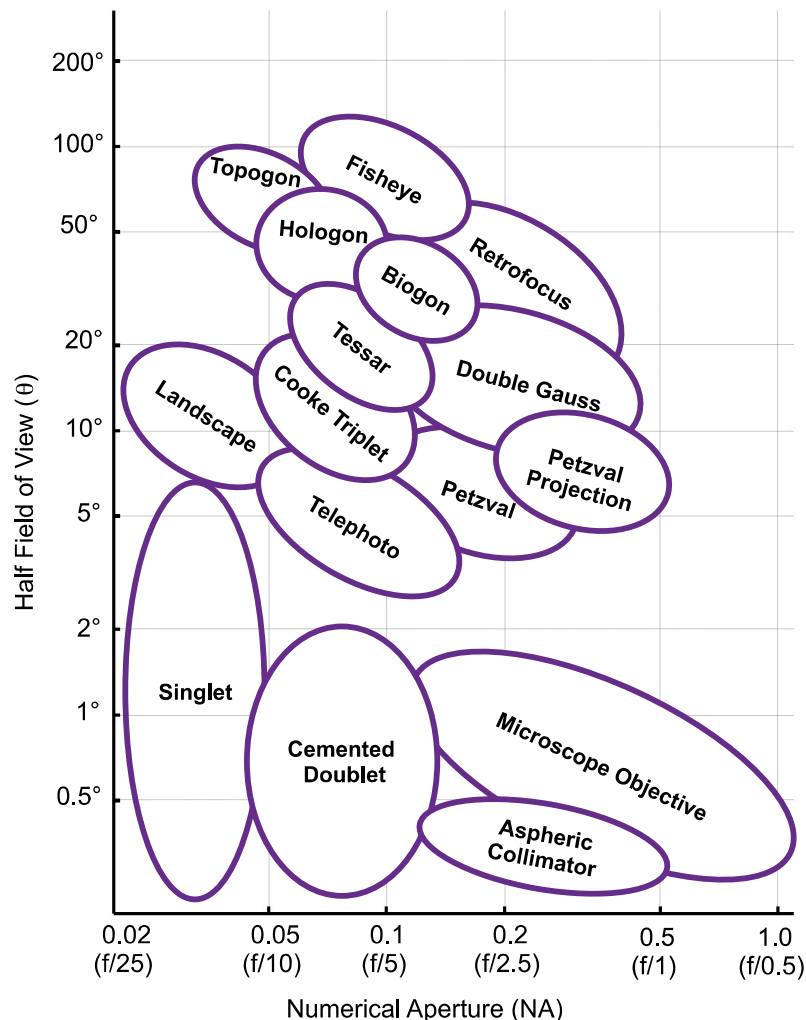
OAP	Off-axis parabola
OAR	Off-axis rejection
OD	Outer diameter (of a lens)
OPD	Optical path difference
OTF	Optical transfer function
p	Pixel pitch in sampled detector arrays
P	Partial dispersion
PDF	Probability distribution function
PSF	Point spread function
PSNIT	Point-source normalized irradiance transmittance
PST	Point-source transmittance
P–V	Peak to valley
Q	Sampling ratio
r	Radial surface coordinate
R , ROC	Radius of curvature
RI	Relative illumination
RMS	Root mean square
RSS	Root sum square
RT	Reflective triplet
s, s'	Object/image distance
SA	Spherical aberration
SLR	Single-lens reflex
t	Thickness or airspace
T	Temperature
TIR	Total indicator runout
TIR	Total internal reflection
TIS	Total integrated scatter
TMA	Three-mirror anastigmat
TML	Three mirror long
u, u'	Paraxial ray angles w.r.t. optical axis
u, u_a	Marginal ray angle w.r.t. optical axis
$\bar{u}, u_b$	Chief ray angle w.r.t. optical axis
UV	Ultraviolet
V	Abbe number
W	Wave aberration function

Glossary of Symbols and Acronyms

W_{ijk}	Wavefront aberration coefficient
WD	Working distance
y, y_a	Marginal ray height at a surface
$\bar{y}, y_b$	Chief ray height at a surface
z	Optical axis
$z(r)$	Surface sag/profile function
Z_n	Zernike polynomial coefficient
β	Lens shape factor
$\Delta\lambda$	Wavelength range or bandwidth
δz	Defocus
ε	Obscuration ratio
$\varepsilon, \varepsilon_x, \varepsilon_y$	Transverse ray error
θ, θ'	Angle of incidence/refraction
θ	Half field of view
θ	Pupil azimuthal coordinate
κ	Conic constant
λ	Wavelength
λ_0	Center wavelength
ρ, ρ_x, ρ_y	Normalized radial pupil coordinate
Φ	System power
ϕ	Element or surface power
ϕ	Merit or penalty function

Selecting a Design Form: Refractive

Aperture and **field size** are the two key system specifications that determine the difficulty/complexity of a design and can therefore be used to identify an appropriate starting design form. If the aperture or field size of a design form is increased outside of its working region, the performance drops off; if the aperture or field size is decreased, the design form is likely to meet the performance requirement but is more complex/costly than necessary. The classic design-form regions indicated below are approximate and do not necessarily represent diffraction-limited performance. Most assume spherical surfaces and are valid over the visible band. Modern designs build on these basic forms, often incorporating aspheres to reduce package size, improve performance, and/or increase the aperture or field size.

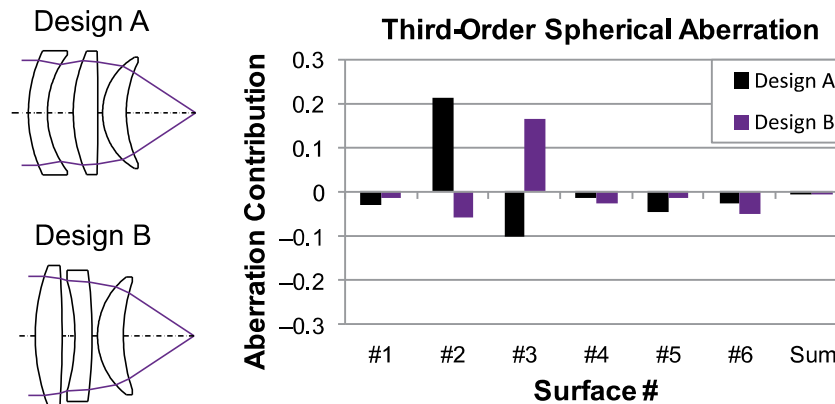


Techniques for Improving an Optical Design

Many techniques exist either to improve an existing lens with inadequate performance or to extend an existing design over new requirements without changing the basic design form. The most common scenario arises when a designer must “push” a **legacy design** to increased aperture and/or larger field (for better resolution/throughput). Such requests often come with a challenging expectation of no significant increase in the physical size of the design. Options available to a designer include:

- **Split** a lens
- **Compound** a lens
- **Aspherize** a surface
- Use a **diffractive** surface
- Raise (or lower) index
- Raise (or lower) V
- Use an abnormal partial dispersion material

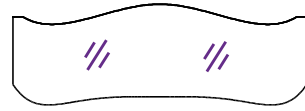
Each of the above techniques seeks to reduce the aberration contribution of a surface/component. A **Seidel** or **Pegel diagram** shows the surface-by-surface aberration contribution and is a key tool in identifying elements or surfaces to target for improvement. It can also be very useful for comparing the sensitivity of different design solutions.



Increasing the aperture or field of an existing design can lead to **ray failures** during lens evaluation and optimization. Examples include **total internal reflection (TIR)** or **ray intercept failures** (where rays physically miss a surface). The solution is to slowly “walk” up to the desired aperture or field in small increments, optimizing the lens at each step.

Aspheres: Design

By definition, **aspheres** are “nonspherical” surfaces. Standard aspheres are rotationally symmetric, but off-axis conic sections and **freeform surfaces** are also referred to as aspheres. Many qualitative terms exist that help describe an aspheric shape (e.g., mild, weak, steep, or **gull wing**). In optical design, aspheres are used to increase performance or reduce the size and weight of a system. Near a pupil, aspheres can be used to correct all orders of spherical aberration. Near an image plane (e.g., on a field lens), they can be used to correct astigmatism or distortion, or achieve telecentricity. Early applications for aspheres included illuminators, infrared systems, and single-wavelength, high-NA, small-field systems like DVD objectives or laser diode collimators.



Dual Gull Wing Asphere
w/ Inflection Points

When optimizing with aspheres, a designer should significantly increase the pupil ray density and, if the asphere is near an image plane, add more field points.

The **sag** of a surface is the displacement (along z) of the surface from its vertex as a function of lateral position (x , y , or radial coordinate r). The traditional **aspheric sag equation** combines a **conic** expression with an even-order polynomial, yielding a rotationally symmetric surface with no vertex discontinuity:

$$\text{sag} = z = \frac{cr^2}{1 + \sqrt{1 - (\kappa + 1)c^2r^2}} + dr^4 + er^6 + fr^8 + gr^{10} + \dots$$

Both the **conic constant** κ and the r^4 coefficient will affect third-order spherical, whereas the higher-order coefficients are useful for correcting higher orders of spherical aberration (in high-NA systems). However, unneeded high-order terms can create oscillatory surfaces and optimization convergence problems. Alternatively, a **Q-type (Forbes) polynomial** aspheric expansion is an orthogonal basis set where the coefficients are linked to aspheric departure and slope, making it more practical for tolerancing and manufacturing.

Choosing Effective Variables

Certain variables are more effective at improving lens performance than others. **Radii of curvature** and **airspace**s are almost always left free to vary during optimization. Packaging or manufacturing constraints (e.g., requirements for a flat surface, equal radii, or working distance) may restrict their range of values.

In contrast, **lens thicknesses** are much less effective variables (a change in a lens thickness is often equivalent to a change in a nearby airspace). Element thicknesses are often kept frozen during a majority of the design process. However, in some cases (e.g., thick-meniscus, Petzval-correcting lenses), the thickness of a lens is an essential variable in improving image quality; thicknesses may also need to be released to meet edge thickness constraints. If allowed to vary, optimizers tend to make lenses very thick (or very thin), slightly improving Petzval with only a small improvement in the merit function.

A lens element whose thickness is chosen to maintain a diameter-to-thickness or **aspect ratio** between 10:1 and 5:1 is often easier and less costly to manufacture.

“Glass” choice is a critical variable for color correction as both the index of refraction and dispersion are dependent on the material choice. Glass differs from most variables as it is a **discrete** rather than a **continuous variable**. **Model** or **fictitious glasses** allow continuous index and Abbe number for optimization, but a real material must eventually be substituted from a **glass map**.

Aspheric coefficients are important variables for aberration correction in modern designs. If possible, aspheric coefficient variables should be enabled during optimization one at a time (starting with the lowest orders), one surface at a time. It is not necessary in most designs to vary the conic constant simultaneously with the fourth-order polynomial coefficient; rather, vary the conic on strong surfaces and the fourth-order term on flatter surfaces.