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Field Guide to **Lens Design**

Julie Bentley
Craig Olson

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Email: books@spie.org

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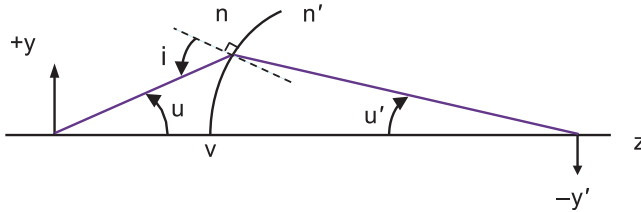
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Sign Conventions

Throughout this **Field Guide**, a set of fully consistent sign conventions is utilized.



- The z axis is the **optical axis** or the axis of symmetry of a rotationally symmetric optical system.
- The y axis is in the plane of the paper, perpendicular to the z axis, and the x axis points directly into the paper, forming a right-handed coordinate system.
- All distances are measured relative to a reference point, line, or plane in a Cartesian sense: **directed distances** above or to the right are positive; below or to the left are negative.
- Angles u are measured from the optical axis to the ray with the smallest of the two angles chosen, while **angle of incidence** i are measured from the normal of the surface to the incident ray.
- Counter-clockwise angles are positive, and clockwise angles are negative.
- The **radius of curvature** of a surface is defined as the directed distance from its vertex to its center of curvature and is therefore positive when the center of curvature is to the right of the surface.
- Light travels from left to right (from $-z$ to $+z$) unless reflected.
- A ' (prime) symbol following a variable denotes a value after refraction at a surface.
- The signs of all indices of refraction following a reflection are reversed.
- To aid in the use of these conventions, all directed distances and angles are identified by arrows with the tail of the arrow at the reference point, line, or plane.

Basic Concepts

A **lens** is often described as a device that creates an image of an object on a detector. More generally, it can be thought of as any system that tries to collect and distribute light in a specified way. Although a lens can consist of a single lens element, it is often composed of multiple lens elements of different shapes and sizes, referred to as a **lens system** or an **optical system**.

Optical design or **lens design** is the process used to find the best set of lens construction parameters (e.g., radii of curvature, thicknesses, airspaces, and materials) that optimizes the overall performance (including the manufacturability) of an optical system.

A **specification document** lists the requirements needed to design a lens system. It defines basic specifications such as object and image location, aperture, field of view, and wavelength range. It contains image quality measures such as spot size, resolution, and distortion. It also includes packaging and environmental requirements such as diameter, length, and temperature.

Optical design software is computer code that aids in the selection and optimization of lens construction parameters and performance evaluation. Given a starting point and a set of variables and constraints, the computer program drives an optical design to a local optimum, as defined by a merit function.

A **lens designer** (or “ray bender”) finds the variations in lens parameters that yield the greatest improvements in optical system performance. Computer optimization and real **ray tracing** (use of Snell’s law to find the position and direction of a ray after refraction or reflection at each lens surface) are key components of the process. A lens designer is also often responsible for developing a specification document (and resolving any conflicts) and identifying engineering trades between performance, packaging constraints, tolerances, cost, and schedule.

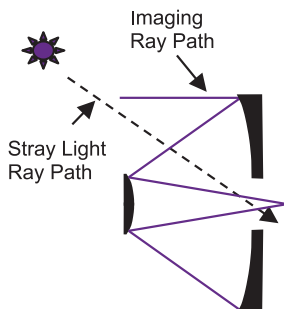
Optical Design Process

The basic **optical design process** is as follows:

- A **specification document** for the optical system is established, and the appropriate type of lens form (e.g., microscope, telescope, camera lens) is selected.
- A starting-point design is chosen from previous projects, historical databases, or patent literature (primarily based on the aperture, field, wavelength, and packaging requirements).
- If an appropriate starting-point design does not exist, designers can choose to start from a **first-order solution** that identifies focal lengths and object/image/pupil locations and sizes using thin lenses and paraxial rays. The first-order solution can be converted to a third-order **thin lens** solution where thin lens parameters such as radius of curvature and index of refraction are chosen to minimize **third-order aberrations**. Thickness is then introduced into the thin lenses to arrive at a **thick lens** starting point.
- The starting-point design is assessed by tracing real rays at multiple wavelengths through the system to analyze the chromatic and higher-order aberrations. Compliance to performance requirements (e.g., image quality, packaging restrictions, fabrication and assembly tolerances, cost) is evaluated.
- If the performance is not acceptable, **optimization** is used to improve the design. A set of variables and constraints is defined, and computer software is used to find design solutions as defined by a **merit function**.
- If the solution is still unacceptable, designers must return to a previous step and iterate until the design meets specifications. This process may require the selection of a different starting-point design and/or requesting a significant change in one or more of the specifications.
- The manufacturability of the design is just as important as the final image quality. Therefore, a complete design process and performance evaluation includes **tolerancing**, **stray light analysis**, and **thermal** and other **environmental analyses**.

Stray Light Analysis

Stray light is any unwanted light that reduces performance by striking the image plane of an optical system. Primary sources of stray light include reflections from uncoated or poorly coated surfaces, surface or bulk scattering, thermal emission, bright out-of-field objects, glints from mechanical structures, diffracted light from edges, and unwanted diffraction orders from gratings.



Stray light can be divided into two main categories: **ghost images** and **veiling glare**. Ghost images have structure (often with sharp edges) and create local image-quality disruptions. Veiling glare produces a diffuse background haze on the image plane, resulting primarily in a loss of overall image contrast.

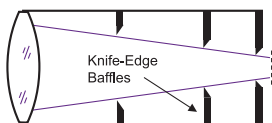
Tracing rays backwards from the detector (or “putting your eye at the detector”) is a highly efficient technique for isolating potential stray light paths and is much more effective than tracing from a source to a detector.

A **stray light analysis** determines both the amount of stray light at the detector and the different paths that it took to get there. If the stray light is large enough to cause a problem, the analysis should also identify any design changes needed to reduce the stray light. Some key metrics used to quantify stray light include **off-axis rejection (OAR)**, **point-source transmittance (PST)**, **point-source normalized irradiance transmittance (PSNIT)**, and **Narcissus-induced temperature difference (NITD)** in infrared systems. The accuracy of a stray light analysis is limited by the availability of source and scatter data, the completeness of the computer model, and the available computer time.

Stray Light Reduction

Identifying potential stray light paths during the design phase is essential to avoiding costly errors in hardware. A **critical object** is any surface that can be seen by the detector, including surfaces that are imaged through lens elements. An **illuminated object** receives power directly from the source and depends on the source location. The overlap between the list of critical and illuminated objects highlight key stray light paths. An object on both lists is called a **first-order stray light path**, which is a major contributor to stray light and should be addressed. **Second-order stray light paths** exist anywhere that light can propagate (transmit, reflect, scatter, or diffract) from an illuminated object to a critical object.

Field stops reduce the number of illuminated objects in a design because objects behind the field stop cannot be seen by the source—only objects in front of the field stop can be illuminated. Similarly, placing the **aperture stop** as close as possible to the detector reduces the number of critical objects in a design since objects in front of the aperture stop cannot be seen by the detector. This approach may require that the aperture stop be relayed from the front of the lens system to the rear because the farther the aperture stop is from a lens, the larger the front elements become in diameter. **Lyot** or **glare stops** are apertures placed in conjugate pupil planes; such stops might need to duplicate any aperture stop obscurations from mounting features for extreme stray light control.



Identified stray light paths can be eliminated by blocking light with **baffles**, **vanes**, and **knife edges**, or by relocating an object so that it is no longer seen by the detector

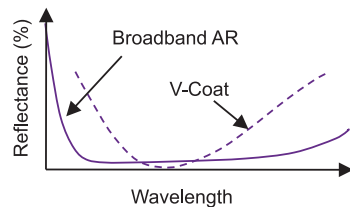
or illuminated by a source. Mechanical surfaces and edges of optical elements can be treated to absorb or scatter light by blackening or roughening. **Rifling** or **threading** barrels and mechanical surfaces is a common and economical way of reducing stray light.

Antireflection (AR) Coatings

Optical surfaces require **antireflection (AR) coatings** to reduce stray light and improve transmission. For an uncoated surface, the amount of **Fresnel reflection** loss depends on the angle of incidence of the light and the index of the lens material. For light normally incident on a surface in air, the reflection loss is ~4% for a visible glass with an index of 1.5. In the infrared spectrum, the loss per uncoated surface can be as much as 36% due to the high index of infrared materials.

Large changes in ray AOIs across a lens surface can lead to highly nonuniform pupil transmission and pupil polarization in high-NA systems. Steep ray angles of incidence on an AR-coated surface will also **blue-shift** the spectral region of a coating, especially coatings with sharp band edges.

The ideal single-layer AR-coating material for a glass-to-air interface has a quarter-wave of optical thickness and an index of refraction equal to the square root of the lens material index.



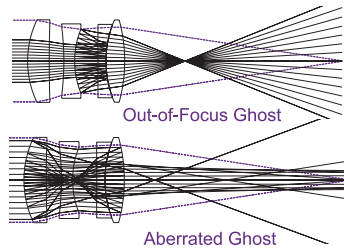
This condition is difficult to achieve in practice. The closest material choice for the visible spectrum is a single quarter-wave layer of MgF_2 (index 1.38), which will reduce the surface reflection from ~4% to ~1% at a single wavelength. More-complex coatings are made of alternating layers of high and low index, each with a thickness equal to a quarter-wave optical thickness. Two- and three-layer **V-coats** can eliminate the reflection at a single wavelength, whereas more-complex **broadband AR (BBAR)** coatings reduce the reflection loss to <0.5% over an extended wavelength band. A variety of coating design optimization software packages exist (very similar to lens design). Most lens design codes will model (but not optimize) thin film stacks for accurate transmission calculations.

Ghost Analysis

Ghosts are a form of stray light from unwanted reflections. Traditional ghosts are double-image artifacts formed by two lens surfaces (**two-bounce ghosts**) with imperfect coatings. However, ghosts can also result from reflections from object, filter, detector, and mechanical surfaces. In interferometer optics, single-reflection ghosts create extra “reference” beams that complicate fringe analysis. In systems with high-power lasers, ghosts can produce an internal focus inside a lens material or on a lens surface that may actually damage the lens. In thermal infrared lenses, **Narcissus** reflections from cooled detector features cause image artifacts. A **pupil ghost** is a special ghost image that echoes the shape of the aperture stop and is typically seen in camera lenses when a bright source (such as the sun) is inside the object field.

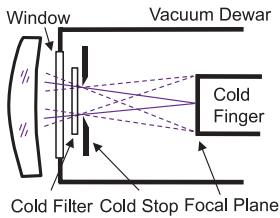
Windows, beamsplitters, concentric meniscus lenses, and optical surfaces with near-normal incident rays are the primary sources of in-focus ghost images.

Most of the potential **ghost images** in a lens system are highly aberrated and out of focus. If the ghost image is significantly defocused from the image plane, it produces a general haze on the detector, reducing image contrast. A



ghost analysis is primarily a graphical technique whereby sequential ray trace routines generate graphical ghost paths that analyze every potential two-bounce reflectance in the optical system and then report the “image quality” of each ghost in terms of spot size, defocus, magnification, and $f/\#$. The relative intensity of a ghost image can be estimated from its number of reflections; however, **nonsequential ray tracing** is required for a quantitative radiometric ghost analysis.

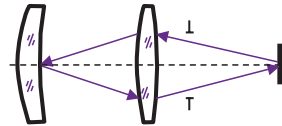
Cold Stop and Narcissus



Many infrared systems require a cryogenically cooled detector that sits in a thermally insulated vacuum **dewar**, reducing background noise and increasing sensitivity. Because the system components also emit the same wavelengths of thermal radiation as

those trying to be imaged by the detector, a **cold shield** is needed to minimize the number of “warm” surfaces (outside of the object scene) that the detector can see. For optimum stray light control, the lens exit pupil should match the detector cold shield in size and location. Imaging the lens stop onto the cold shield forms a **cold stop**, and if imaged perfectly, the system is said to have 100% **cold shield efficiency**.

Surfaces inside the dewar (e.g., the focal plane and the cold stop) are at significantly different temperatures than the scene imagery, and their reflections from an optical surface will form “cold” Narcissus ghost images. Such images are either diffuse background noise or sharp image artifacts varying in field or time. Retroreflection due to a small marginal ray angle-of-incidence at a surface or image reflection due to a small marginal ray height are primary sources of Narcissus. The **YNI product** combines these into a paraxial quantity that can be used to optimize the lens or locate baffles. Staring detectors allow a **nonuniformity correction (NUC)** to calibrate out static reflections, but any lens motion or environmental changes after NUC will induce Narcissus. The **NITD** is the sum of reflected energy from all optical surfaces.



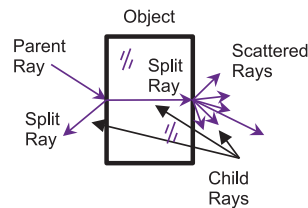
Techniques for minimizing **Narcissus** include anti-Narcissus coatings, baffles, tilting flat windows and filters, and designing with Narcissus ray constraints.

Nonsequential Ray Tracing

Nonsequential ray tracing (NRT) is an extremely powerful analysis technique for evaluating stray light. Unlike standard **sequential ray tracing** in which rays intercept surfaces only once and in a given order, NRT allows a ray to “see” all of the surfaces in a system simultaneously and the ray interacts with the first surface it meets. It is possible for a ray to intersect a single surface multiple times. NRT is also widely used to design and optimize **illumination** and other **nonimaging systems**.

For accurate results, many orders of magnitude more rays need to be traced with NRT than sequential ray traces. As a result, stray light analysis can be time consuming and computationally expensive.

A stray light analysis with NRT requires three components: **sources** that generate rays, objects that interact with rays, and **receivers** that collect the rays and quantify the resulting irradiance or intensity distributions. Key features that can be enabled depending on computation limitations are **ray scattering** and **ray splitting**, which split energy between a **parent ray** and multiple **child rays**. The sum of the transmittance, reflectance, scattering, and absorption on a surface should equal unity. Ray databases that include all ray-surface data can be saved for subsequent filtering and analysis.



NRT models are typically much more complex than sequential optical surface design models and can include:

- multiple sources with rays propagating in any direction;
- mechanical features such as lens mounts, barrels, apertures, baffles, and vanes;
- **absorption** and **scattering** from bulk materials; and
- absorption and scattering from mechanical and optical surfaces (ground, polished, coated, or painted).

Scattering and BSDF

Optical and mechanical surfaces have a finite **surface roughness** that can induce light **scattering**.



The direction and amount of scattered light depend on the incoming ray wavelength, polarization, and angle of incidence. Because the scattered light is a potential source of stray light, a complete stray light analysis requires accurate scatter models for each surface. Ideal scatter models assume that the scatter is either all concentrated in the **specular direction** (reflected angle governed entirely by Snell's law) or is perfectly **Lambertian** (diffuse surface with the same reflected radiance over all viewing angles). Real surface scatter usually lies somewhere between these two extremes, often with most of the light scattered "around" the specular reflection direction.

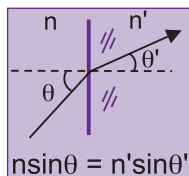
The **bidirectional scattering distribution function (BSDF)** indicates how specular or diffuse a surface is as a function of both the 2D incident angle (θ_i, ϕ_i) and the 2D scattering angle (θ_o, ϕ_o):

$$BSDF(\theta_i, \phi_i; \theta_o, \phi_o) = \frac{L}{E} \left(sr^{-1} \right).$$

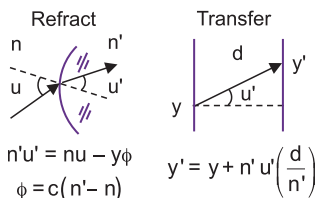
The BSDF is defined as exiting radiance divided by incident irradiance and is centered around the specular angle defined by $\theta_i = \theta_r$. A Lambertian surface has a constant BSDF for all angles of incidence. The reflective and transmissive versions of the BSDF are the **BRDF** and **BTDF**, respectively. A **scatterometer** is used to measure angle-resolved BSDF, BRDF, and BTDF. **Isotropic** surfaces, such as pitch-polished lenses, scatter light equally in all azimuthal directions, simplifying the BSDF function. **Anisotropic** surfaces, such as diffraction gratings, diamond-turned mirrors, or brushed-metal surfaces, have inherently azimuthal directionality. **Total integrated scatter (TIS)** is the integral of the BSDF and is a common scalar metric for total surface scattering without any angular resolution information.

Snell's Law and Ray Tracing

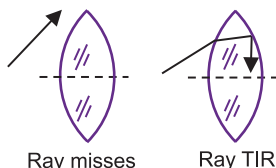
Snell's law (of **refraction**) is the primary equation used in ray tracing. It governs the change in direction of a ray at a dielectric interface between two materials. Snell's law relates two angles in one plane of incidence; a full 3D ray trace typically uses **direction cosines**, the ray's unit vector projection onto each coordinate axis. Because of the sine functions in Snell's law, ray tracing calculations through multiple surfaces become highly nonlinear for large angles. Snell's law of reflection can also be applied to a reflecting surface if the sign of the index of the incident material is reversed after the **reflection**.



Once the ray is refracted or reflected at a surface, it must be **translated** (or **propagated**) to the next surface, changing its height (or location in 3D) without changing its angle. **Paraxial ray tracing** assumes that for small angles, $\sin(\theta)$ is approximately equal to θ ; this significantly simplifies ray tracing equations [replacing the $n \sin(\theta)$ with $n\theta$ in Snell's law]. The resulting **paraxial refraction** and a **paraxial transfer equation** allow visual **brick** (or **ynu**) diagrams or matrix math to be set up quickly to calculate the first-order properties of an optical system.

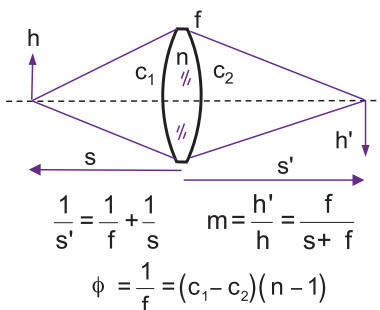


Ray failures generally occur when either a ray fails to intercept the next sequential surface or the ray undergoes total internal reflection (TIR) at a surface. Optical design codes have significant difficulty evaluating a lens system if reference rays (e.g., the chief ray) fail to trace.



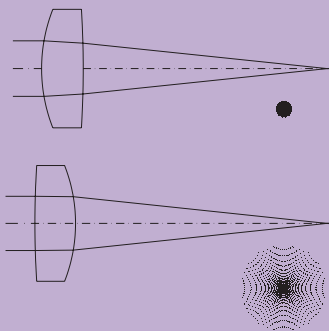
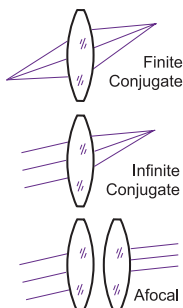
Focal Length, Power, and Magnification

Focal length is a fundamental first-order property of a lens. For a thin lens, given the object distance and focal length, the **Lens maker's equation** can be used to quickly find the image distance. The focal length also determines the **magnification** (relative size) between the object and image for



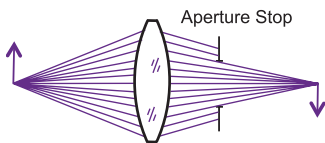
a given object position. The **power** of a lens is the reciprocal of its focal length. For a **thin lens**, the power is related solely to its two curvatures and its index. For a thick lens, an **effective focal length (EFL)** is defined that equals the distance between its **focal** and **principal planes** in either object or image space.

The powered surface of a **plano-convex singlet** made from glass ($n \sim 1.5$) has a convex radius approximately equal to half its focal length. For the best performance, the surface should be oriented with the convex side facing the collimated light or laser beam.



Objects and images form **conjugate** planes. A **finite conjugate** system has both a finite object and a finite image distance. An **infinite conjugate** system has either the object or the image located at infinity. In an **afocal** system, both the object and image are located at infinity. The performance of a lens designed for a specific conjugate usually degrades when used at other conjugates.

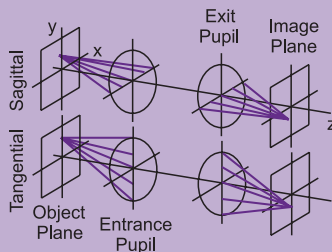
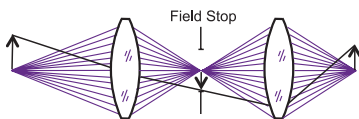
Aperture Stop and Field Stop



The **aperture stop** (often shortened to just **stop**) or **stop surface** is the *single* aperture in the lens system that limits the bundle of light

that propagates through the system from the *axial* object point. In the absence of vignetting, the ray bundles from other object points also fill the aperture stop (“pivoting” about the center of the stop). The aperture stop is typically a mechanical surface (for good edge definition) and can be located anywhere in the optical system except at the object, the image, or an internal image. The size of the aperture stop sets the system $f/\#$ and NA. For objects at infinity, the aperture stop limits the input beam diameter.

A **ray fan** is a “slice” of rays that emerge from a single field point and pass through a line in the pupil. The **tangential fan** (Y-fan or **meridional fan**) passes through the pupil’s y axis, and the **sagittal fan** (or X-fan) passes through the pupil’s x axis.



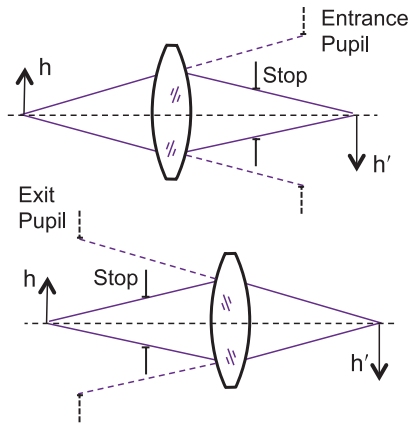
Field stops also limit the amount of light that can propagate through the system from the object

plane to the image plane by setting the maximum object height from which a ray bundle can emerge and still pass through the lens. Field stops are typically the image (or the object) surface; however, if the system has an internal image plane, a field stop may be located there (usually for stray light control), and because this plane is conjugate with the image, reticles, crosshairs, or linear scales are placed at the internal field stop to be simultaneously imaged on the focal plane.

Entrance and Exit Pupils

Wavefront performance for imaging lenses is often measured at the exit pupil. The exit pupil and the image plane form a Fourier transform pair under Fresnel propagation. Optical design codes calculate **point spread functions (PSFs)** and other diffraction-based metrics using a **fast-Fourier transform (FFT)** of the exit pupil wavefront.

The physical stop surface is often buried in a lens system and difficult to access, leading to the definition of pupils. The images of the aperture stop formed by the lens elements before and after the stop surface are called the **entrance** and **exit pupils**, respectively. If the stop is at the first (last) surface, it is also the entrance (exit) pupil.



The entrance (exit) pupil appears to limit the incoming (outgoing) bundle of rays in object (image) space. **Pupil matching** is a critical consideration when combining two independently designed optical systems. The entrance pupil of the second system should have the same position and diameter as the exit pupil of the first system to avoid losing light and reducing the FOV through vignetting. The entrance and exit pupils are images of each other forming conjugate planes, and, consequently, they can have **pupil aberrations**.

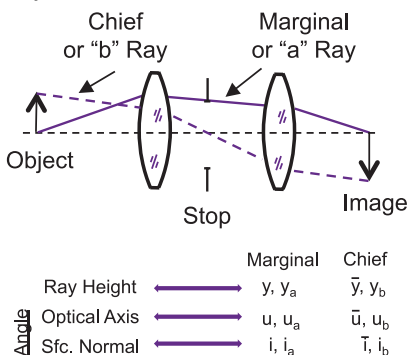
Similar to entrance and exit pupils, internal field stops can be imaged by the lens elements on either side of the field stop, forming **entrance** and **exit windows**. However, not all lenses have internal images and, therefore, entrance and exit windows.

Marginal and Chief Rays

Given the surface curvatures, material indices, and element thicknesses, the **marginal** and **chief rays** are the only two **reference rays** that need to be traced to calculate all first-order properties and third-order aberrations of a lens system.

The marginal ray starts at the base of the object (the on-axis, $H = 0$, field point) and passes through the edge of the aperture stop. The marginal ray locates all image positions, including any intermediate images; it also defines the edge of the ray bundle, and, therefore, the maximum sizes of the entrance and exit pupils.

The chief ray originates from the edge of the object (the full-field, $H = 1$, field point) and passes through the center of the aperture stop. The chief ray defines the maximum FOV of the lens system.



Pupils exist wherever the chief ray crosses the optical axis (the entrance and exit pupil are typically virtual; the chief ray needs to be extended “back” until it crosses the optical axis). The image size is determined by the height of the chief ray at the image plane.

The chief ray intercept on the focal plane may not define the center of the energy distribution for a given field point. In this case, the spot **centroid** or “center of mass” is a better metric for determining true field position at an image plane. Optical design programs allow a designer to reference various performance metrics (e.g., RMS spot diameter, distortion) from either the chief ray location or the centroid location.