Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Lens Design I

Lecture 2: Properties of optical systems I

2024-04-18

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Preliminary Schedule - Lens Design I 2023

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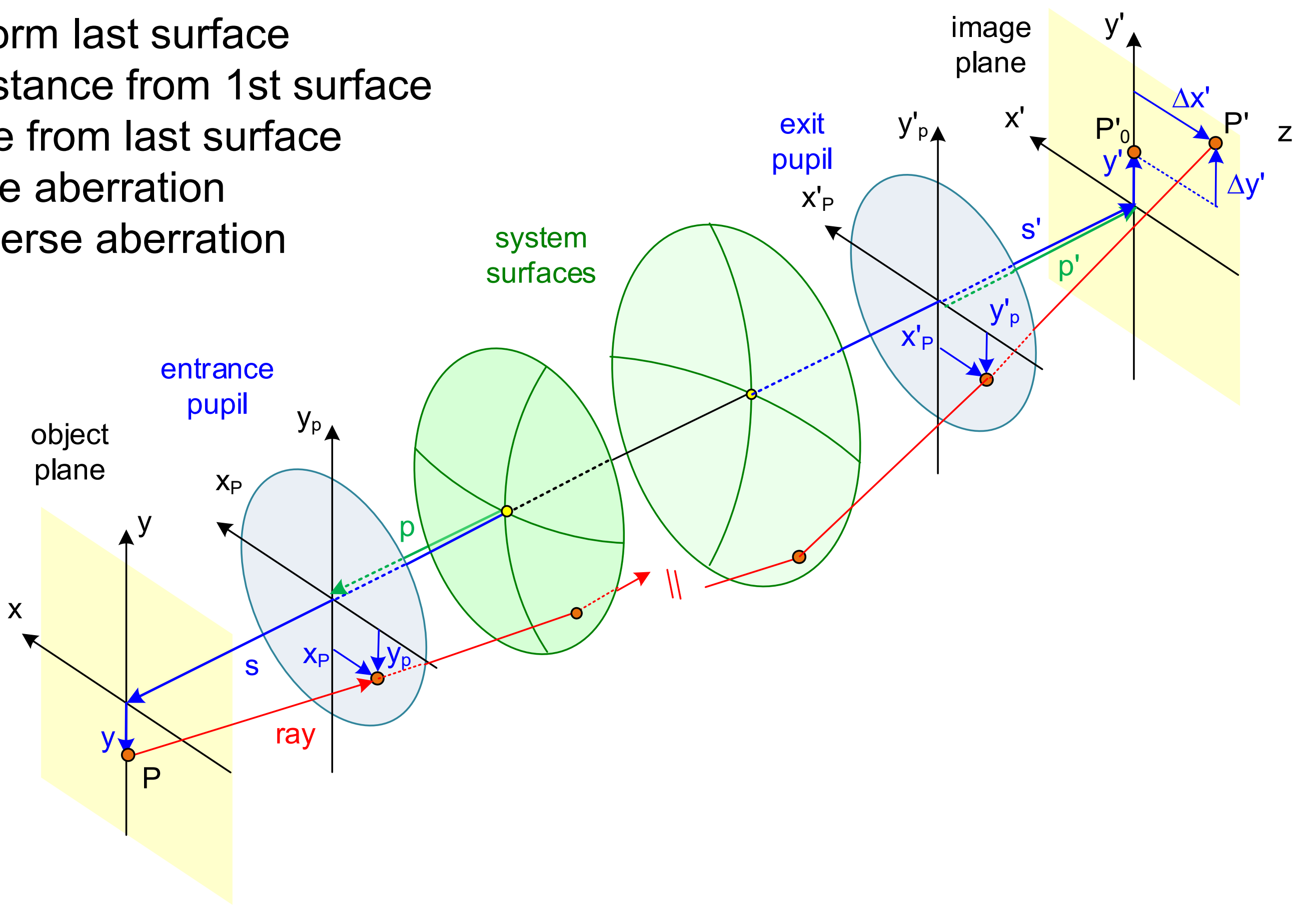
1	04.04.	Basics	Zhang	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, coordinates, System description, 3D geometry, aperture, field, wavelength
2	18.04.	Properties of optical systems I	Tang	Diameters, stop and pupil, vignetting, layouts, materials, glass catalogs, raytrace, ray fans and sampling, footprints
3	25.04.	Properties of optical systems II	Tang	Types of surfaces, cardinal elements, lens properties, Imaging, magnification, paraxial approximation and modelling, telecentricity, infinity object distance and afocal image, local/global coordinates
4	02.05.	Properties of optical systems III	Tang	Component reversal, system insertion, scaling of systems, aspheres, gratings and diffractive surfaces, gradient media, solves
5	16.05.	Advanced handling I	Tang	Miscellaneous, fold mirror, universal plot, slider, multiconfiguration, lens catalogs
6	23.05.	Aberrations I	Zhang	Representation of geometrical aberrations, spot diagram, transverse aberration diagrams, aberration expansions, primary aberrations
7	30.05.	Aberrations II	Zhang	Wave aberrations, Zernike polynomials, measurement of quality
8	06.06.	Aberrations III	Tang	Point spread function, optical transfer function
9	13.06.	Optimization I	Tang	Principles of nonlinear optimization, optimization in optical design, general process, optimization in Zemax
10	20.06.	Optimization II	Zhang	Initial systems, special issues, sensitivity of variables in optical systems, global optimization methods
11	27.06.	Correction I	Zhang	Symmetry principle, lens bending, correcting spherical aberration, coma, astigmatism, field curvature, chromatical correction
12	04.07.	Correction II	Zhang	Field lenses, stop position influence, retrofocus and telephoto setup, aspheres and higher orders, freeform systems, miscellaneous

Contents

Notations for an Optical System

x, y	object coordinates, especially object height
x', y'	image coordinates, especially image height
x_p, y_p	coordinates of entrance pupil
x'_p, y'_p	coordinates of exit pupil
s	object distance form 1st surface
s'	image distance form last surface
p	entrance pupil distance from 1st surface
p'	exit pupil distance from last surface
$\Delta x'$	sagittal transverse aberration
$\Delta y'$	meridional transverse aberration



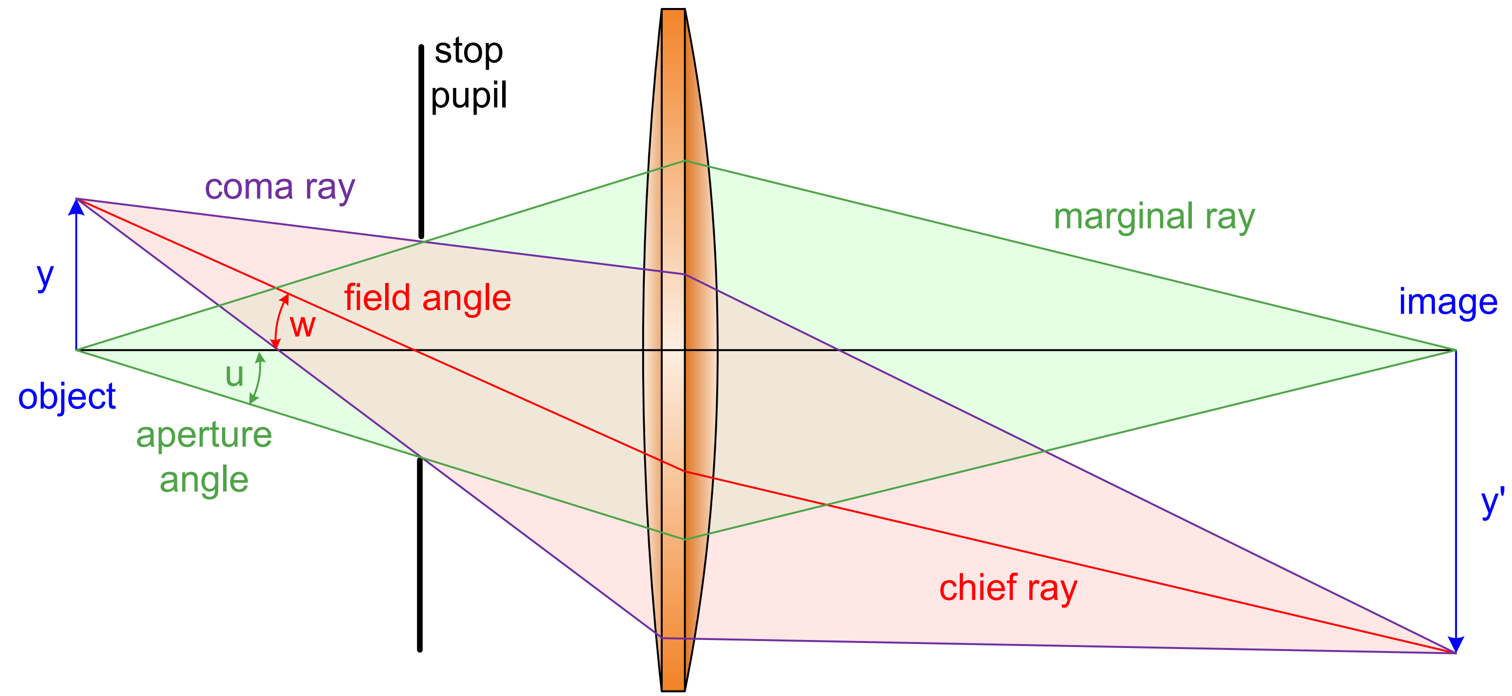
Optical system stop

- Stop: determine chief ray and marginal ray

  1. chief ray angle w

  2. aperture cone angle u

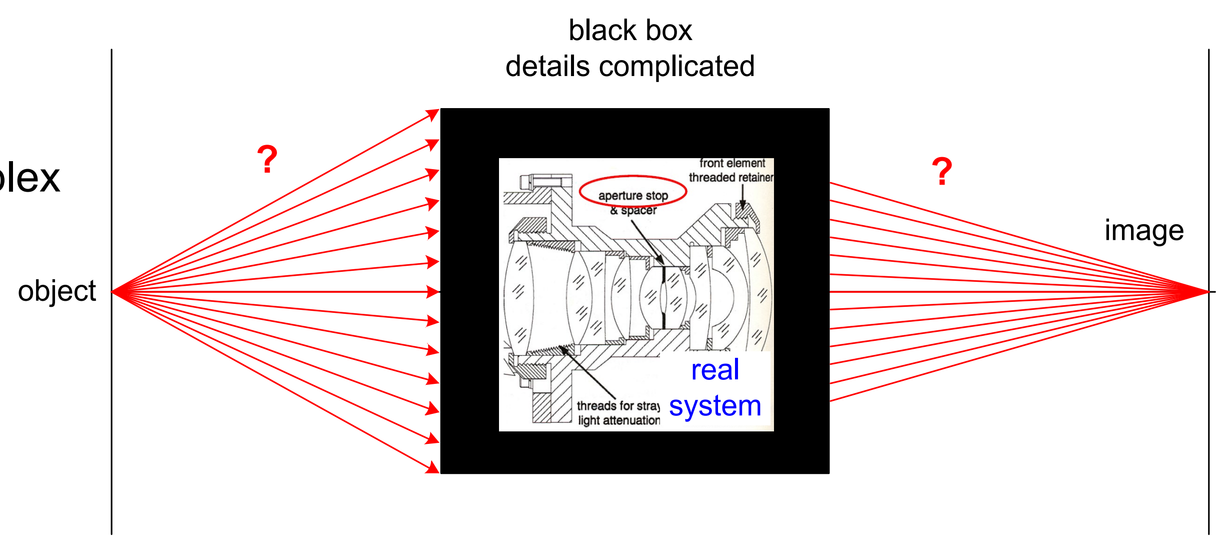
- The chief ray gives the center line of the oblique ray cone of an off-axis object point
- The coma rays limit the off-axis ray cone
- The marginal rays limit the axial ray cone



Optical system stop

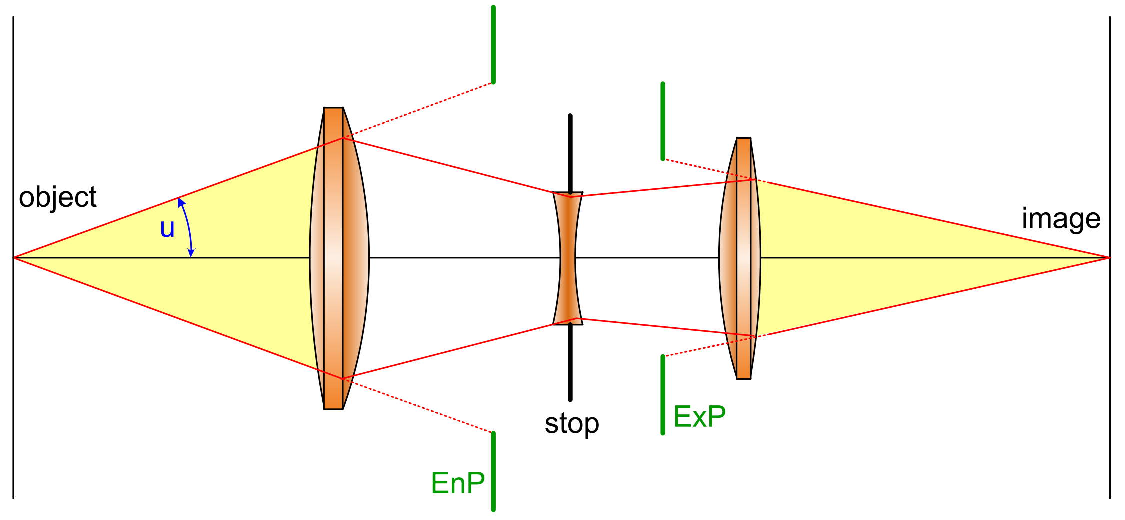
- The physical stop defines the aperture cone angle u

- The real system may be complex



- The entrance pupil fixes the acceptance cone in the object space

- The exit pupil fixes the acceptance cone in the image space



Ref: Julie Bentley

Properties of the pupil

Relevance of the system pupil :

- Brightness of the image
  Transfer of energy

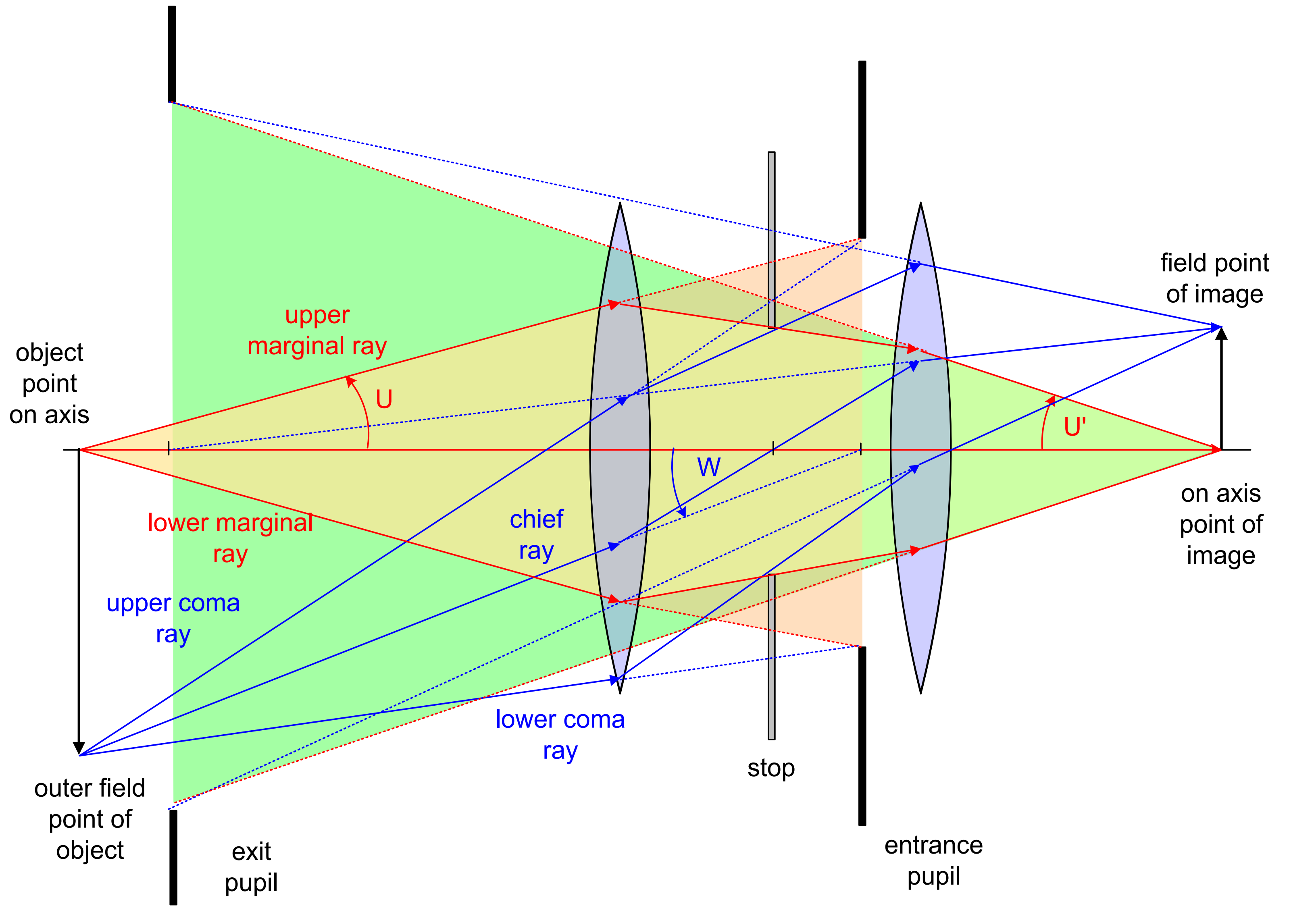
- Resolution of details
  Information transfer

- Image quality
  Aberrations due to aperture

- Image perspective
  Perception of depth

- Compound systems:
  matching of pupils is necessary, location and size

Entrance and exit pupil

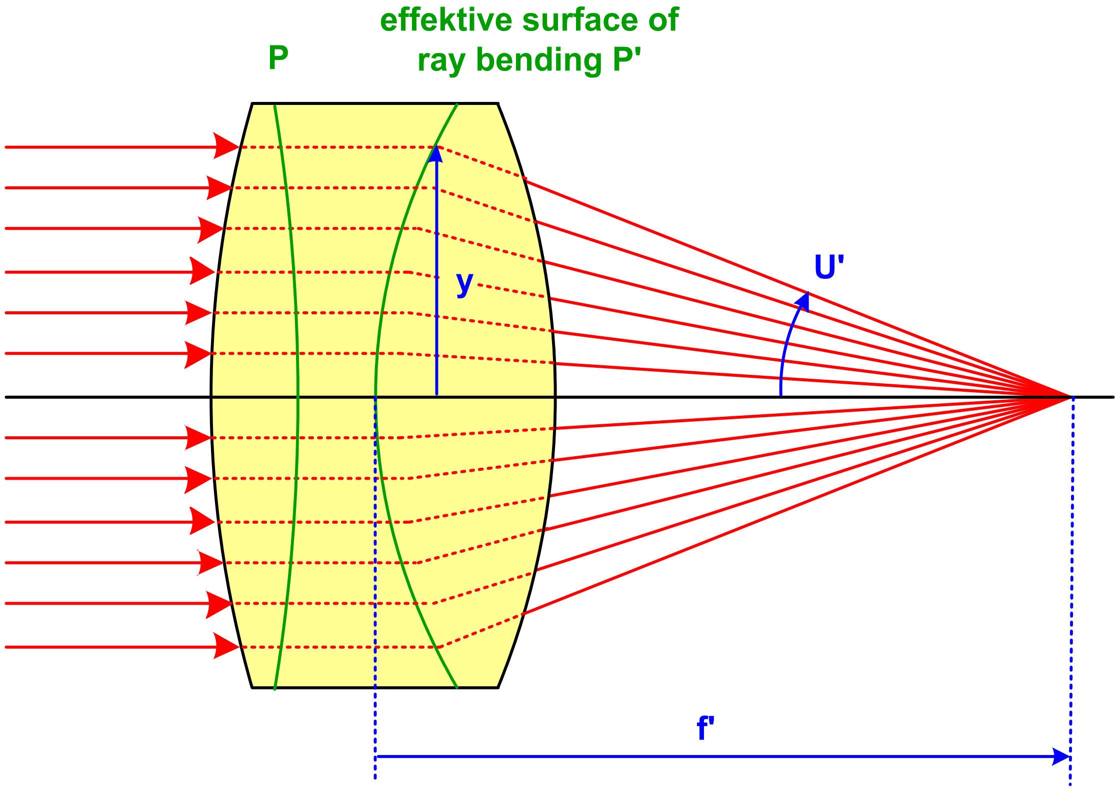


Principal Surface

- Generalization of paraxial picture:
  Principal surface works as effective location of ray bending

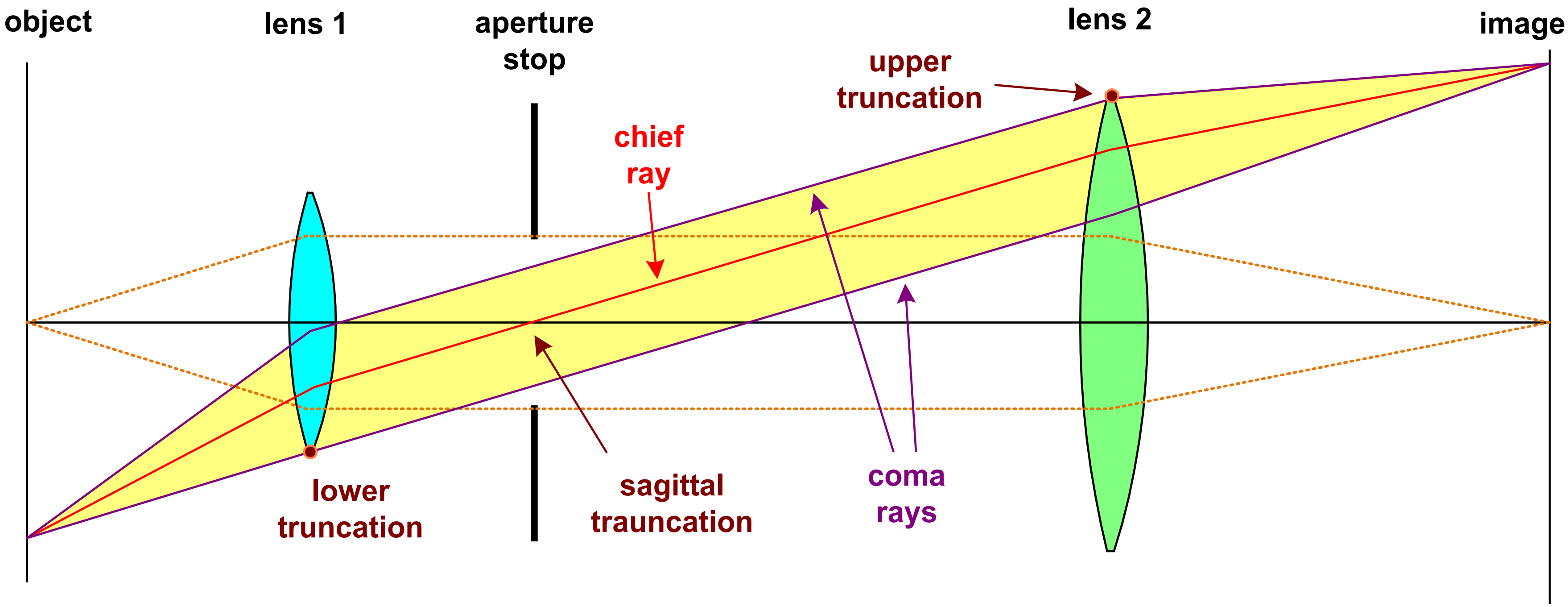
- Paraxial approximation: plane

- Real systems with corrected sine-condition (aplanatic): principal sphere



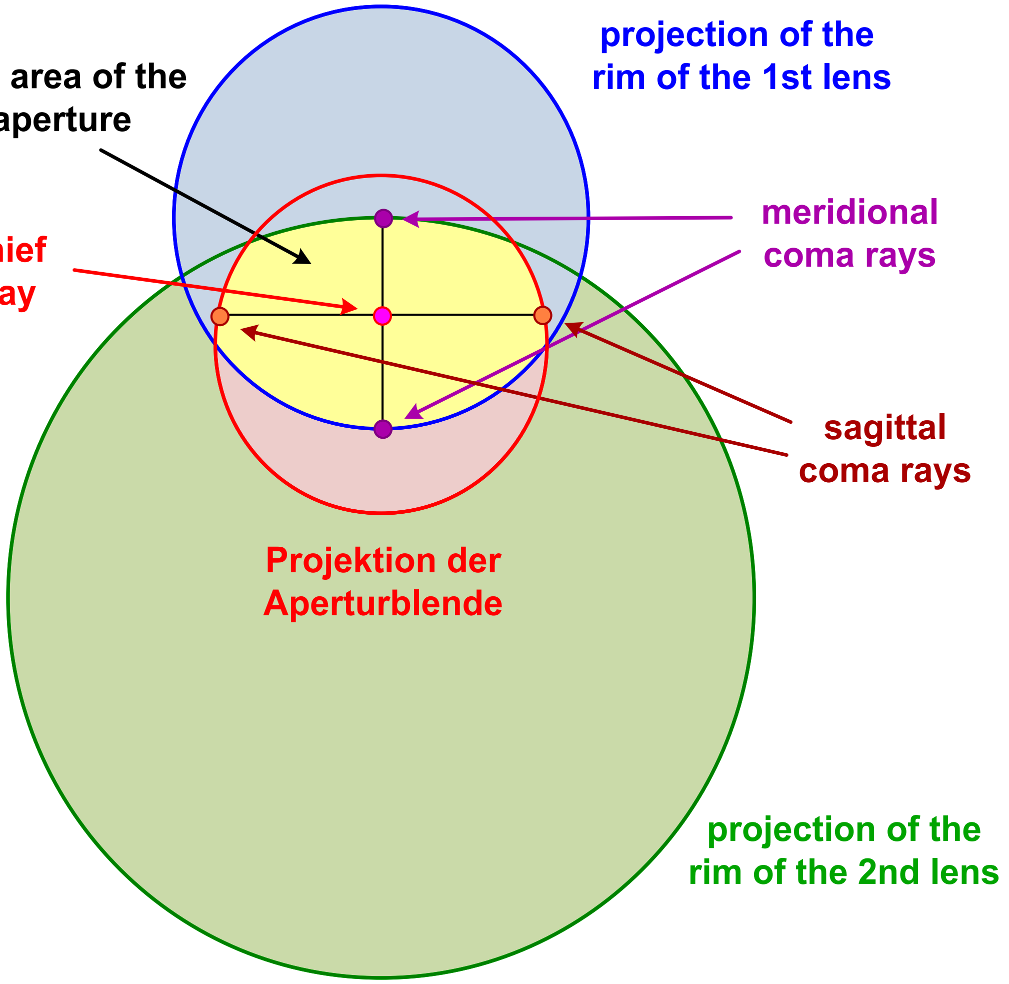
Vignetting

- 3D-effects due to physical sizes
- Truncation of the ray dundles at different surfaces for the upper and the lower part of the cone



Vignetting

- Truncation of the light cone with asymmetric ray path for off-axis field points
- Intensity decrease towards the edge of the image
- Definition of the chief ray: ray through energetic centroid
- Vignetting can be used to avoid uncorrectable coma aberrations in the outer field
- Effective free area with extrem aspect ratio: anamorphic resolution



Optical materials

- Important types of optical materials:
  1. Glasses
  2. Crystals
  3. Liquids
  4. Plastics, cement
  5. Gases
  6. Metals

- Optical parameters for characterization of materials
  1. Refractive index, spectral resolved $n(\lambda)$
  2. Spectral transmission $T(\lambda)$
  3. Reflectivity R
  4. Absorption
  5. Anisotropy, index gradient, eigenfluorescence,…

- Important non-optical parameters
  1. Thermal expansion coefficient
  2. Hardness
  3. Chemical properties (resistence,…)

Test wavelengths

λ in [nm]	Name	Color	Element
248.3		UV	Hg
280.4		UV	Hg
296.7278		UV	Hg
312.5663		UV	Hg
334.1478		UV	Hg
365.0146	i	UV	Hg
404.6561	h	violett	Hg
435.8343	g	blau	Hg
479.9914	F'	blau	Cd
486.1327	F	blau	H
546.0740	e	grün	Hg
587.5618	d	gelb	He
589.2938	D	gelb	Na
632.8			HeNe-Laser
643.8469	C'	rot	Cd
656.2725	C	rot	H
706.5188	r	rot	He
852.11	s	IR	Cä
1013.98	t	IR	Hg
1060.0			Nd:YAG-Laser

Dispersion and Abbe number

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- Description of dispersion:

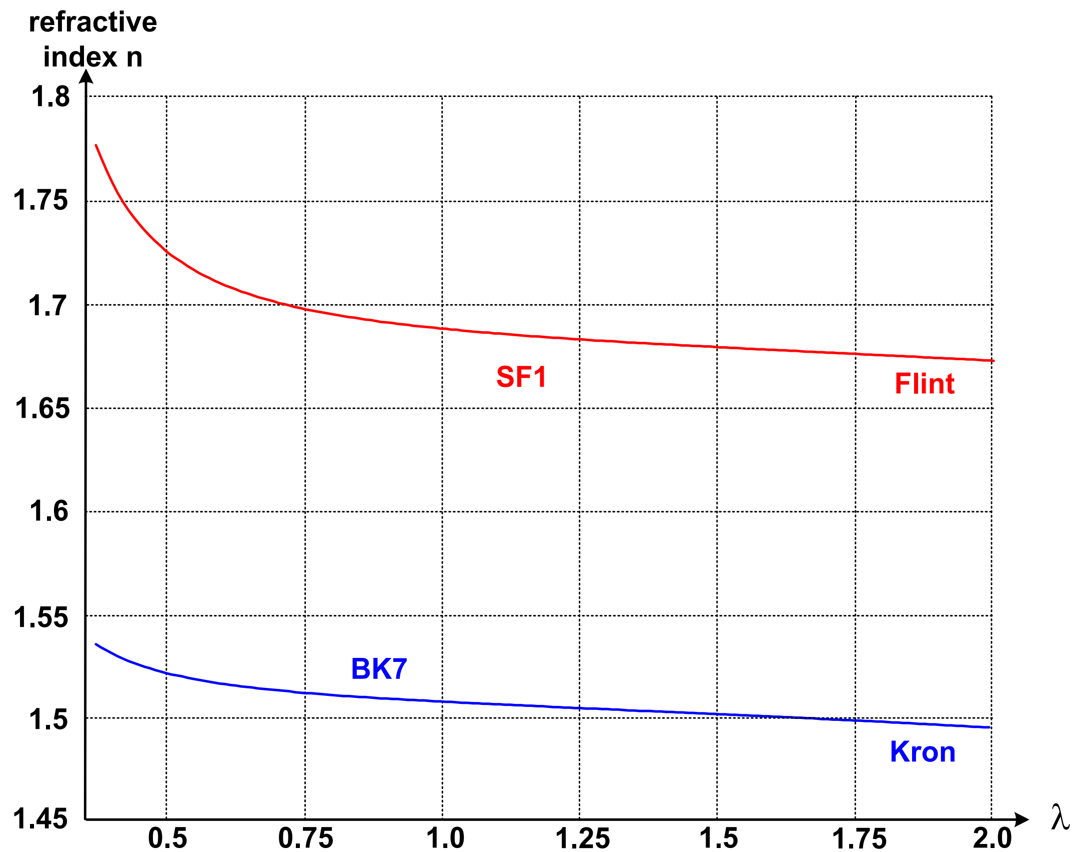
  Abbe number $$\nu(\lambda) = \frac{n(\lambda) - 1}{n_{F'} - n_{C'}}$$

- Visual range of wavelengths:

$$\nu_e = \frac{n_e - 1}{n_{F'} - n_{C'}}$$

- Typical range of glasses
  ν_e = 20 ...120

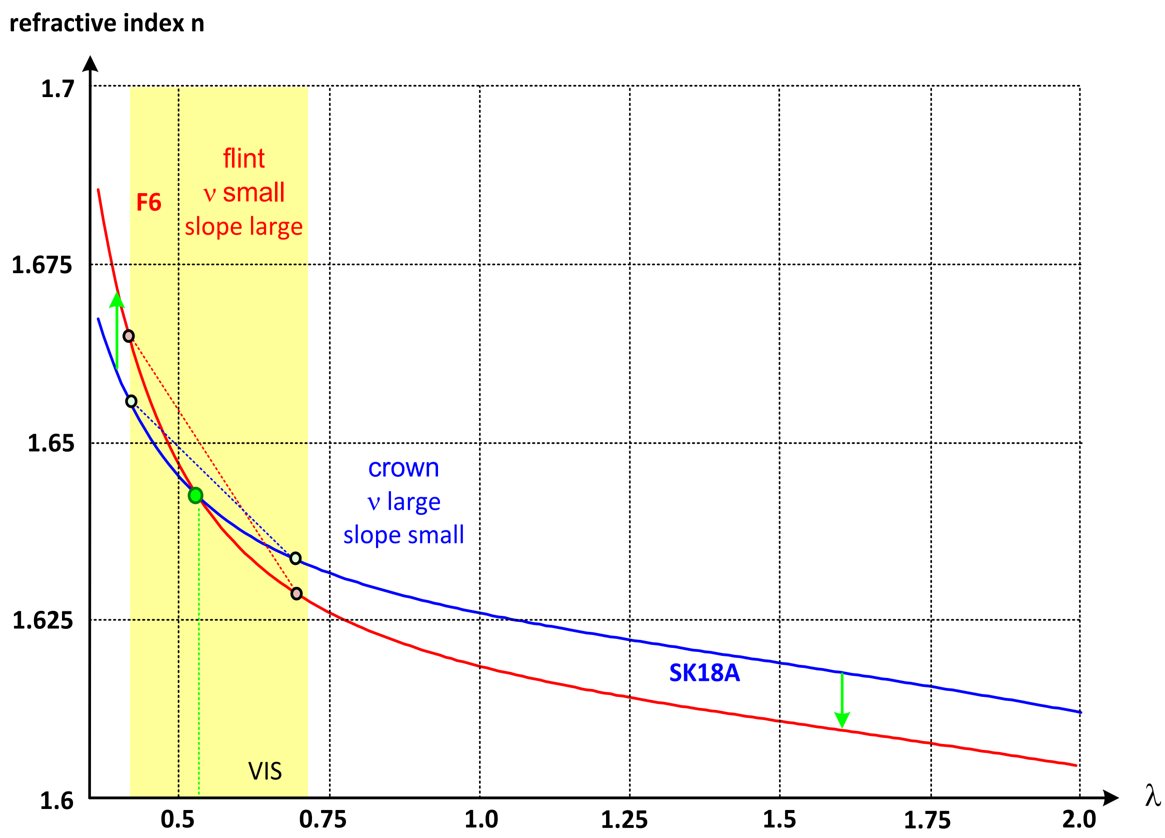
- Two fundamental types of glass:
  Crown glasses:
  n small, ν large
  Flint glasses
  n large, ν small



Dispersion

Material with different dispersion values:

- Different slope and curvature of the dispersion curve
- Stronger change of index over wavelength for large dispersion
- Inversion of index sequence at the boundaries of the spectrum possible



Dispersion formulas

- Schott formula
  empirical

$$n=\sqrt{a_o+a_1\lambda^2+a_2\lambda^{-2}+a_3\lambda^{-4}+a_4\lambda^{-6}+a_5\lambda^{-8}}$$

- Sellmeier
  Based on oscillator model

$$n(\lambda)=\sqrt{A+B\frac{\lambda^2}{\lambda^2-\lambda_1^2}+C\frac{\lambda^2}{\lambda^2-\lambda_2^2}}$$

- Bausch-Lomb
  empirical

$$n(\lambda)=\sqrt{A+B\lambda^2+C\lambda^4+\frac{D}{\lambda^2}+\frac{E\lambda^2}{(\lambda^2-\lambda_o^2)+\frac{F\lambda^2}{\lambda^2-\lambda_o^2}}}$$

- Herzberger
  Based on oscillator model

$$n(\lambda)=a_o+a_1\lambda^2+\frac{a_2}{\lambda^2-\lambda_o^2}+\frac{a_3}{\left(\lambda^2-\lambda_o^2\right)^2}$$

$$mit\quad \lambda_o=0.168\ \mu m$$

- Hartmann
  Based on oscillator model

$$n(\lambda)=a_o+\frac{a_1}{a_3-\lambda}+\frac{a_4}{a_5-\lambda}$$

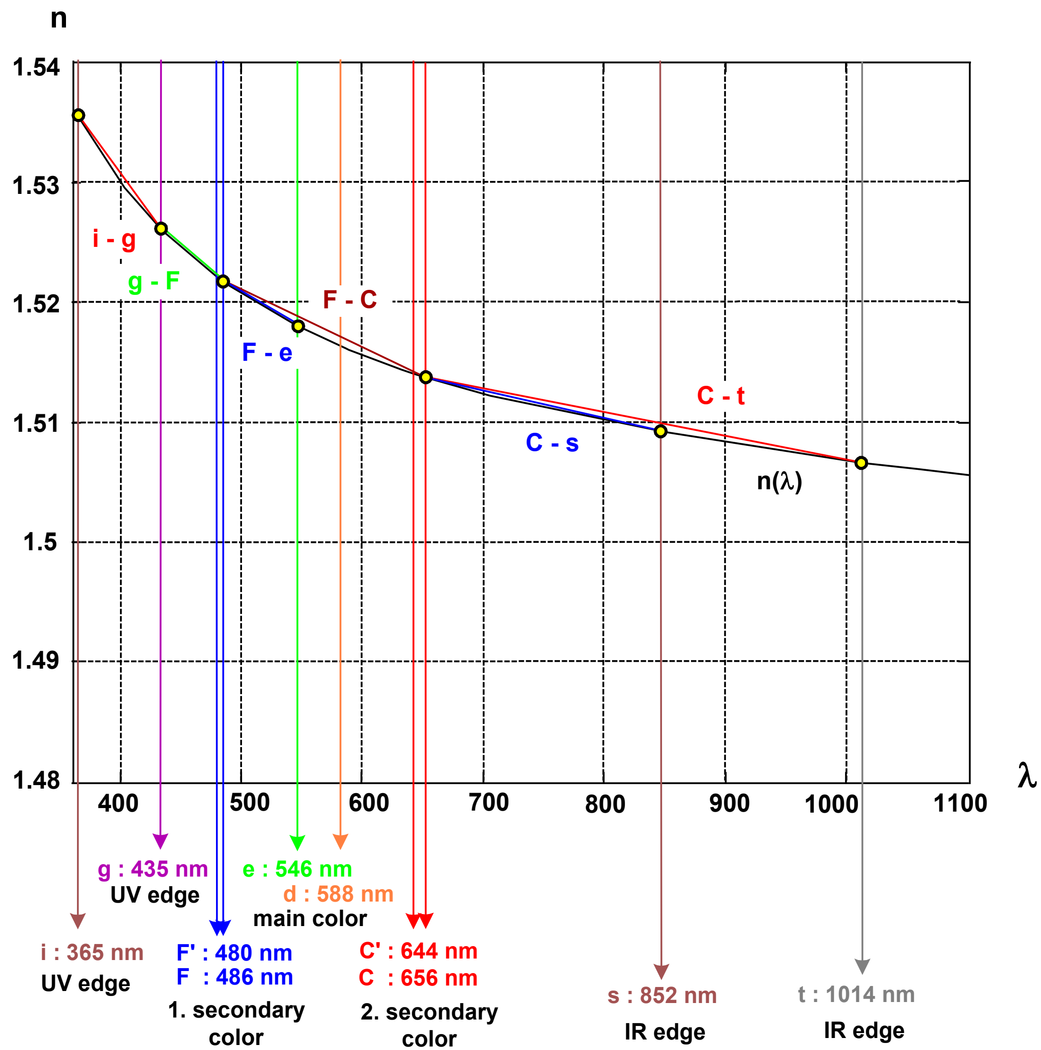
Relative partial dispersion

- Relative partial dispersion :
  Change of dispersion slope with λ
- Definition of local slope for selected wavelengths relative to secondary colors

$$P_{\lambda_1\lambda_2} = \frac{n(\lambda_1) - n(\lambda_2)}{n_{F'} - n_{C'}}$$

- Special selections for characteristic ranges of the visible spectrum

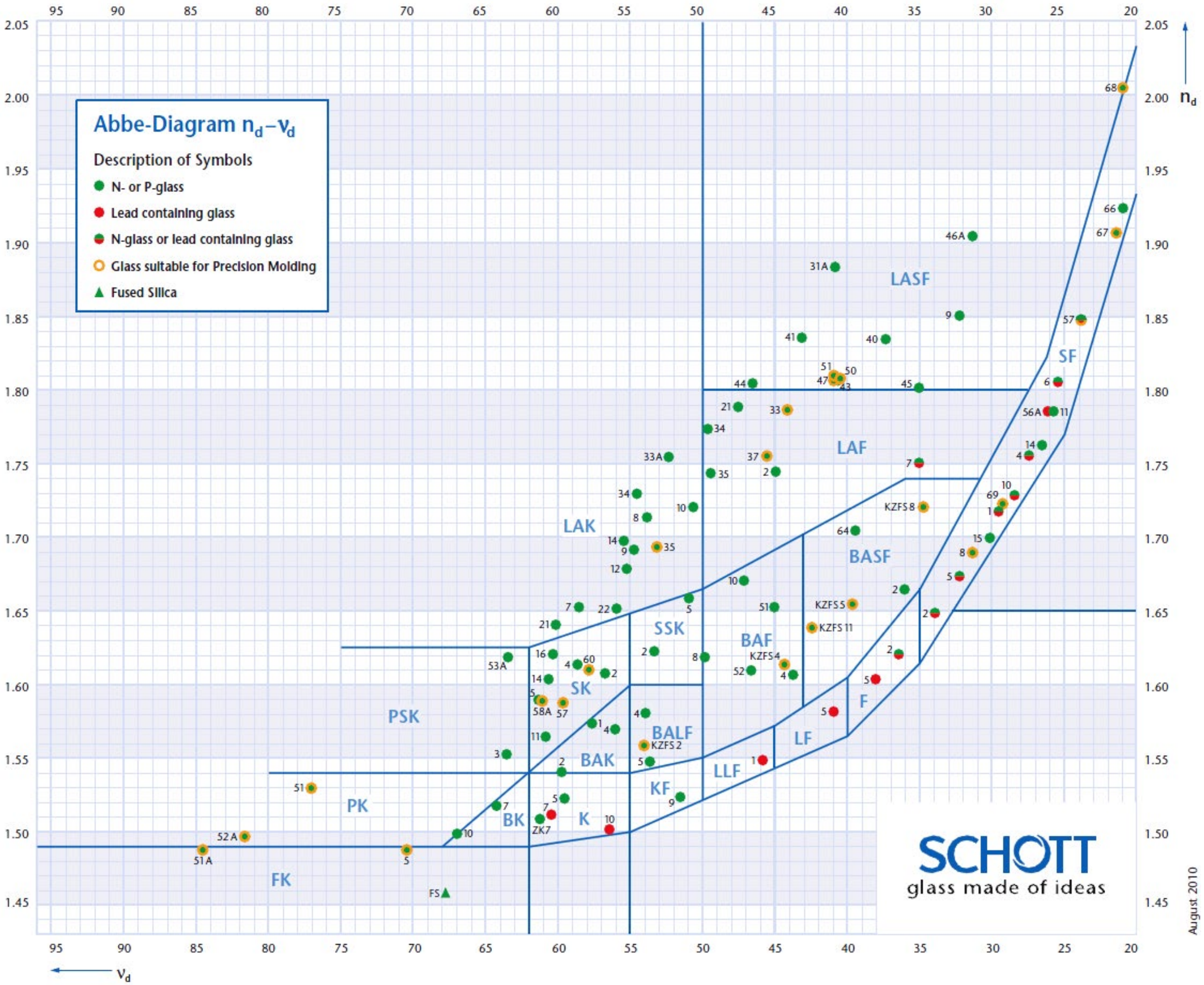
λ = 656 / 1014 nm far IR
λ = 656 / 852 nm near IR
λ = 486 / 546 nm blue edge of VIS
λ = 435 / 486 nm near UV
λ = 365 / 435 nm far UV



Glass diagram

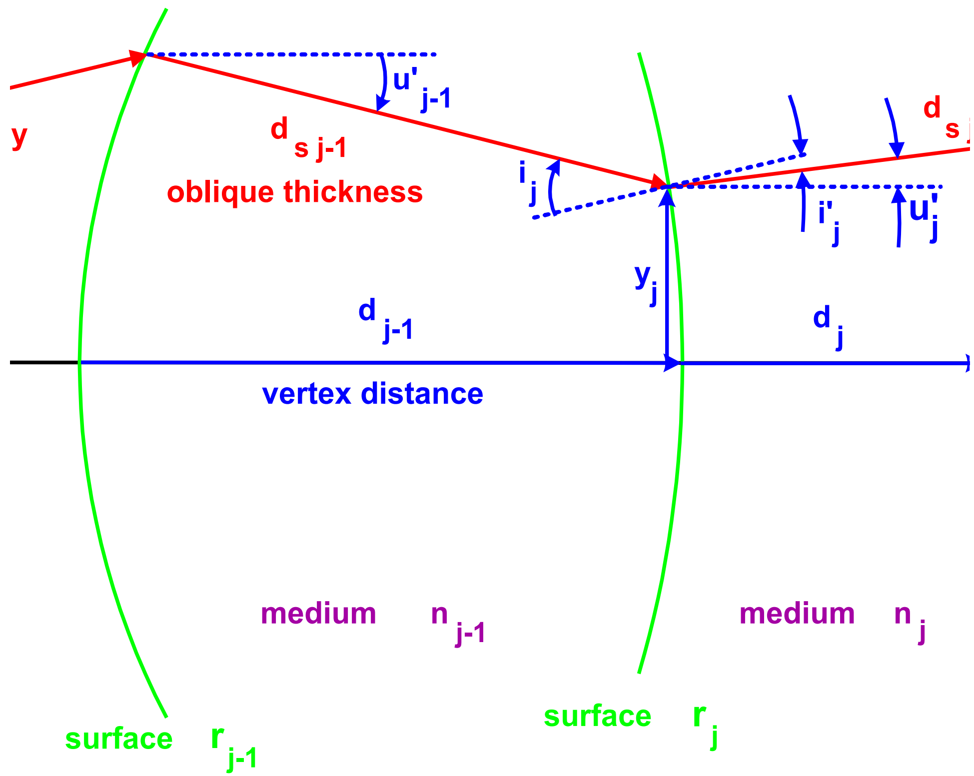
- Usual representation of glasses:
  diagram of refractive index vs dispersion n(ν)

- Left to right:
  decreasing Abbe number
  Increasing dispersion

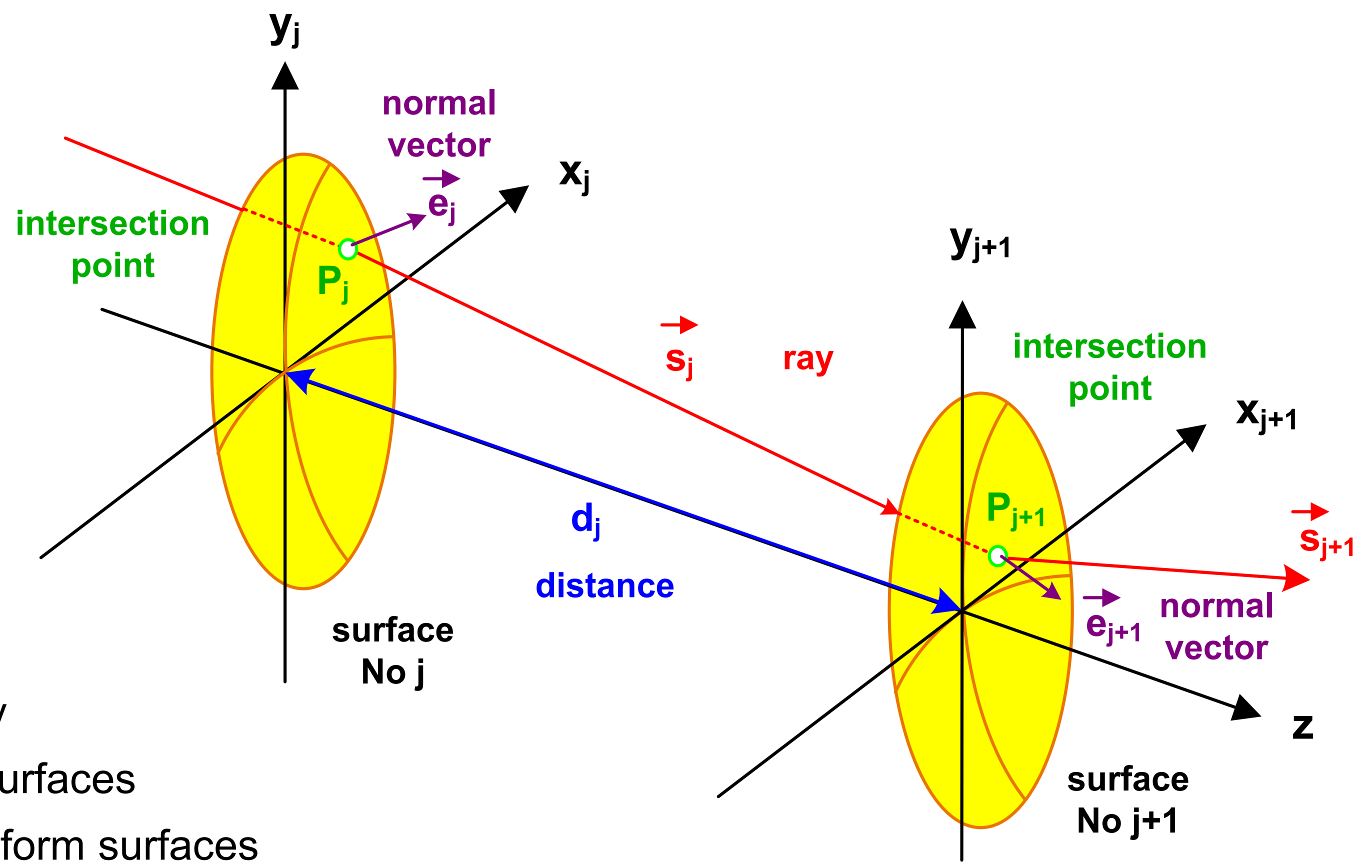


Scheme of raytrace

- Ray: straight line between two intersection points
- System: sequence of spherical surfaces
- Data: - radii, curvature c=1/r
  - vertex distances
  - refractive indices
  - transverse diameter
- Surfaces of 2nd order:
  Calculation of intersection points
  analytically possible: fast
  computation



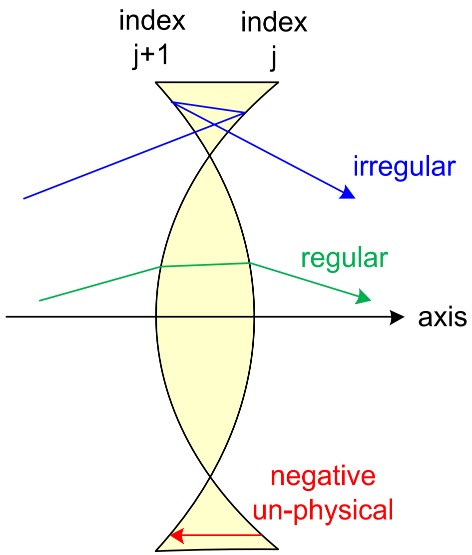
Vectorial raytrace

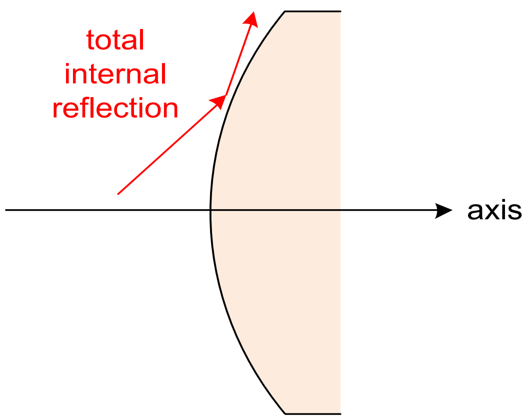


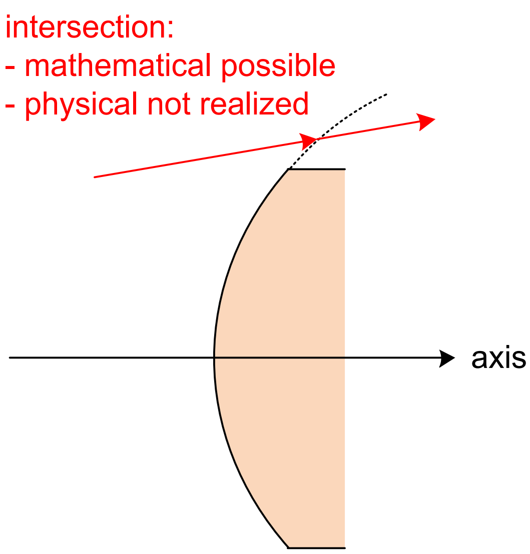
- General 3D geometry
- Tilt and decenter of surfaces
- General shaped free form surfaces
- Full description with 3 components
- Global and local coordinate systems

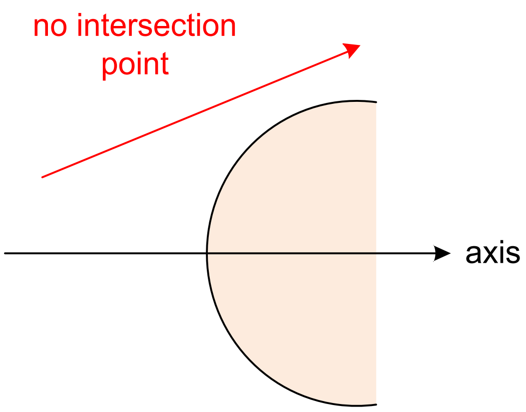
Raytrace errors

- Vignetting/truncation of ray at finite sized diameter:
  can or can not considered (optional)
- No physical intersection point of ray with surface
- Total internal reflection
- Negative edge thickness of lenses
- Negative thickness without mirror-reflection
- Diffraction at boundaries



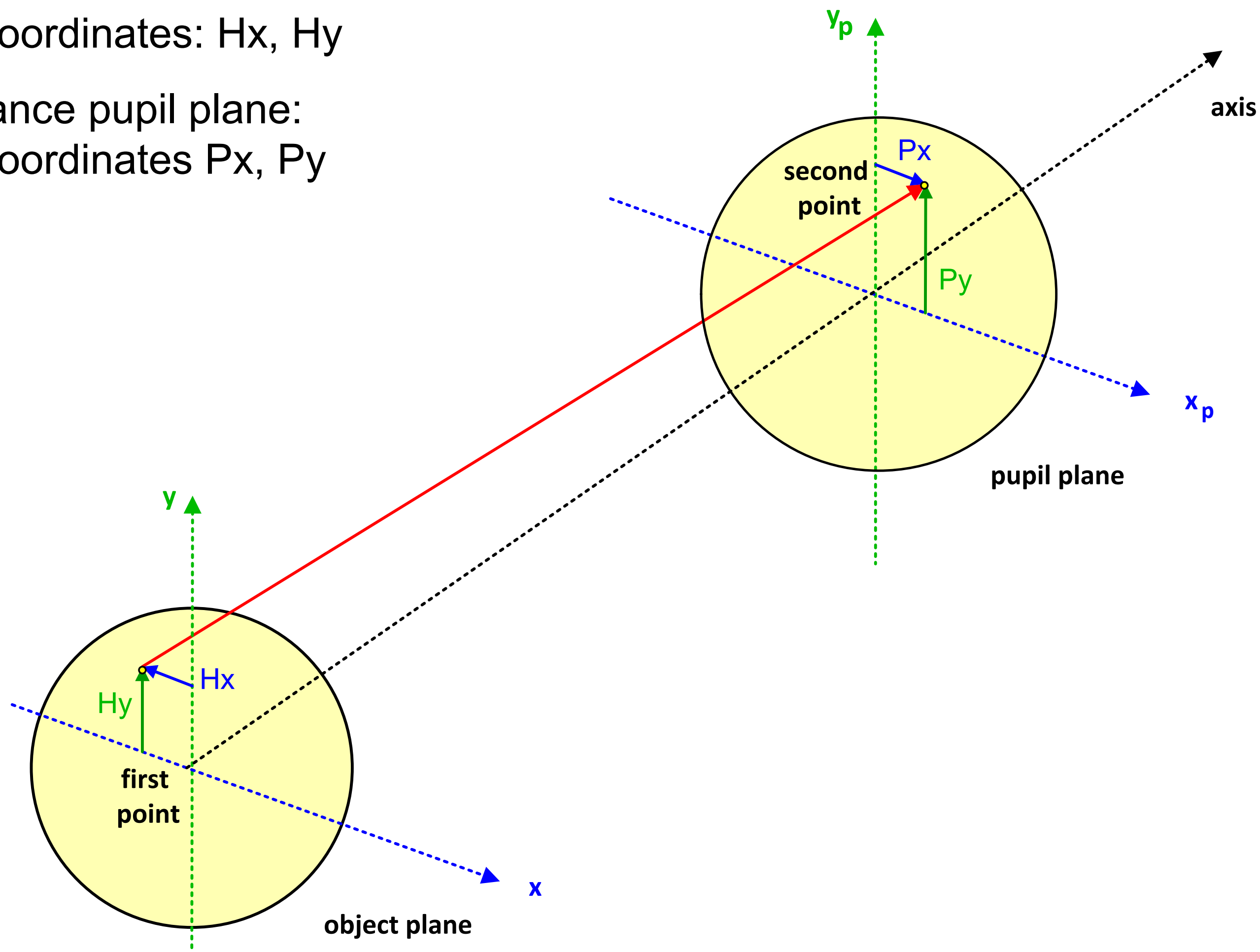






Single Ray Selection

- Definition of a single ray by two points
- First point in object plane:
  relative normalized coordinates: Hx, Hy
- Second point in entrance pupil plane:
  relative normalized coordinates Px, Py



Raytrace in Zemax

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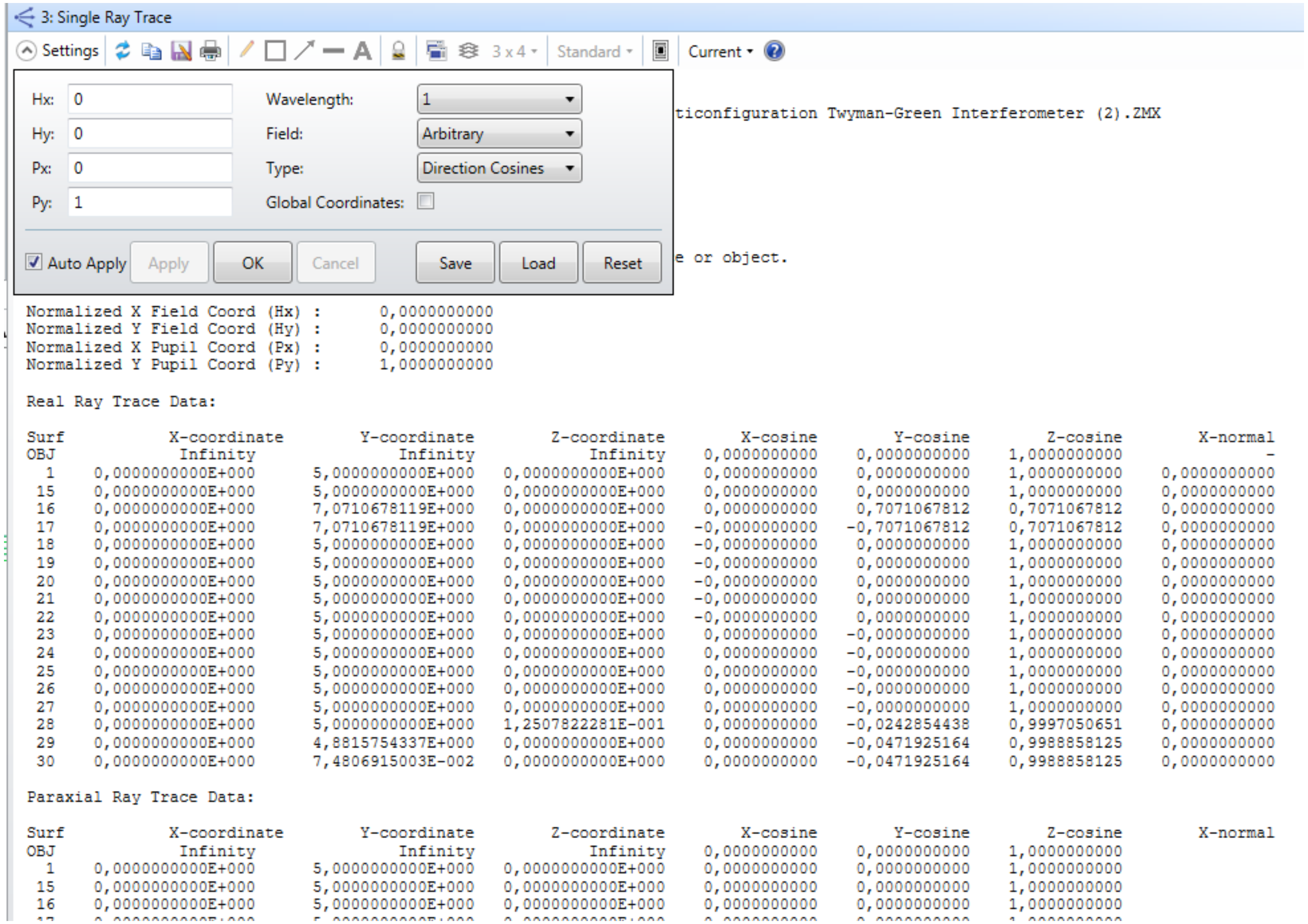
- Selection of 2 points on the ray on object and entrance pupil plane
- Real and paraxial rays are tabulated
- Coordinate reference can be selected to be local or global



Normalized X Field Coord (Hx) : 0,0000000000
Normalized Y Field Coord (Hy) : 0,0000000000
Normalized X Pupil Coord (Px) : 0,0000000000
Normalized Y Pupil Coord (Py) : 1,0000000000

Real Ray Trace Data:

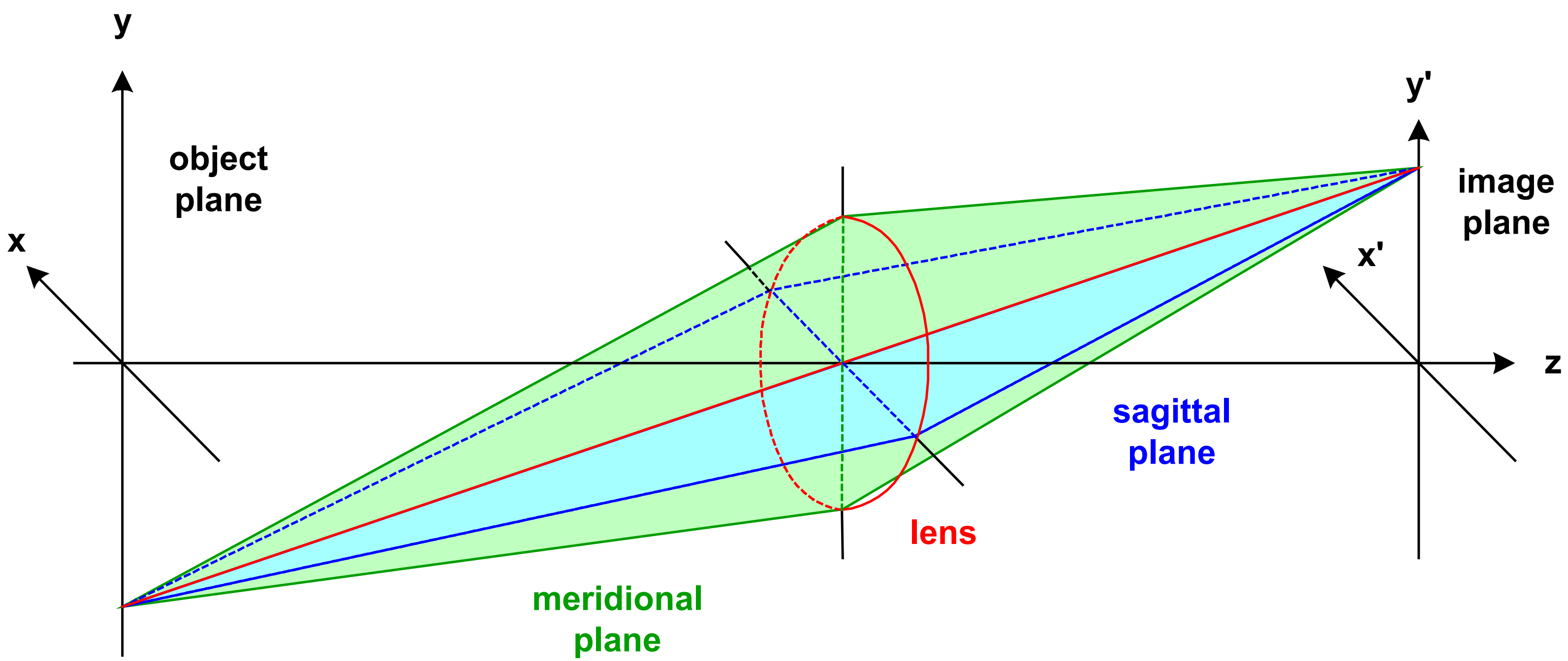
Surf	X-coordinate	Y-coordinate	Z-coordinate	X-cosine	Y-cosine	Z-cosine	X-normal
OBJ	Infinity	Infinity	Infinity	0,0000000000	0,0000000000	1,0000000000	-
1	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	0,0000000000	1,0000000000	0,0000000000
15	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	0,0000000000	1,0000000000	0,0000000000
16	0,0000000000E+000	7,0710678119E+000	0,0000000000E+000	0,0000000000	0,7071067812	0,7071067812	0,0000000000
17	0,0000000000E+000	7,0710678119E+000	0,0000000000E+000	-0,0000000000	-0,7071067812	0,7071067812	0,0000000000
18	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	-0,0000000000	0,0000000000	1,0000000000	0,0000000000
19	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	-0,0000000000	0,0000000000	1,0000000000	0,0000000000
20	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	-0,0000000000	0,0000000000	1,0000000000	0,0000000000
21	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	-0,0000000000	0,0000000000	1,0000000000	0,0000000000
22	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	-0,0000000000	0,0000000000	1,0000000000	0,0000000000
23	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	-0,0000000000	1,0000000000	0,0000000000
24	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	-0,0000000000	1,0000000000	0,0000000000
25	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	-0,0000000000	1,0000000000	0,0000000000
26	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	-0,0000000000	1,0000000000	0,0000000000
27	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	-0,0000000000	1,0000000000	0,0000000000
28	0,0000000000E+000	5,0000000000E+000	1,2507822281E-001	0,0000000000	-0,0242854438	0,9997050651	0,0000000000
29	0,0000000000E+000	4,8815754337E+000	0,0000000000E+000	0,0000000000	-0,0471925164	0,9988858125	0,0000000000
30	0,0000000000E+000	7,4806915003E-002	0,0000000000E+000	0,0000000000	-0,0471925164	0,9988858125	0,0000000000

Paraxial Ray Trace Data:

Surf	X-coordinate	Y-coordinate	Z-coordinate	X-cosine	Y-cosine	Z-cosine	X-normal
OBJ	Infinity	Infinity	Infinity	0,0000000000	0,0000000000	1,0000000000	
1	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	0,0000000000	1,0000000000	
15	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	0,0000000000	1,0000000000	
16	0,0000000000E+000	5,0000000000E+000	0,0000000000E+000	0,0000000000	0,0000000000	1,0000000000	

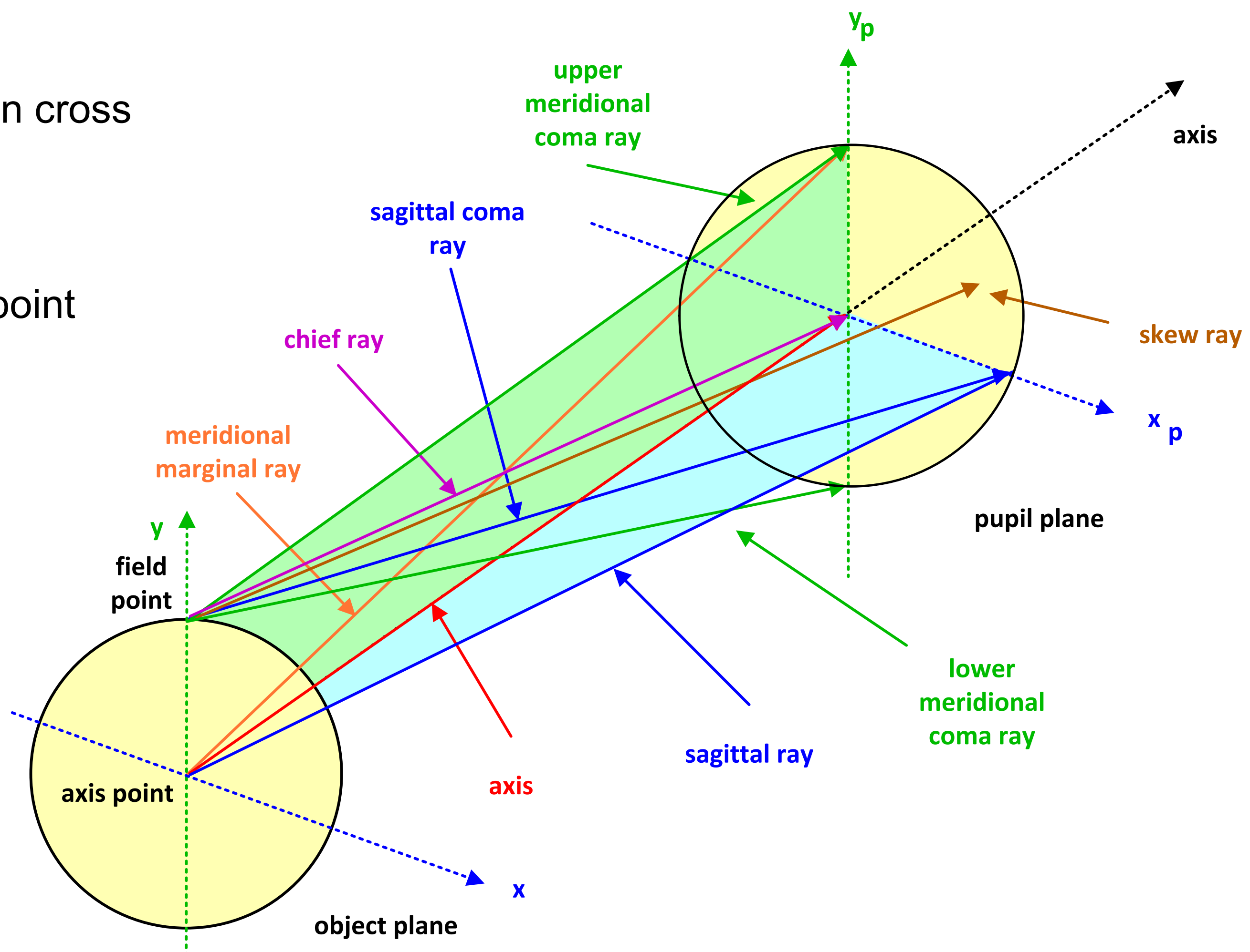
Tangential and sagittal plane

- Off-axis object point:
  1. Meridional plane / tangential plane / main cross section plane
     contains object point and optical axis
  2. Sagittal plane:
     perpendicular to meridional plane through object point



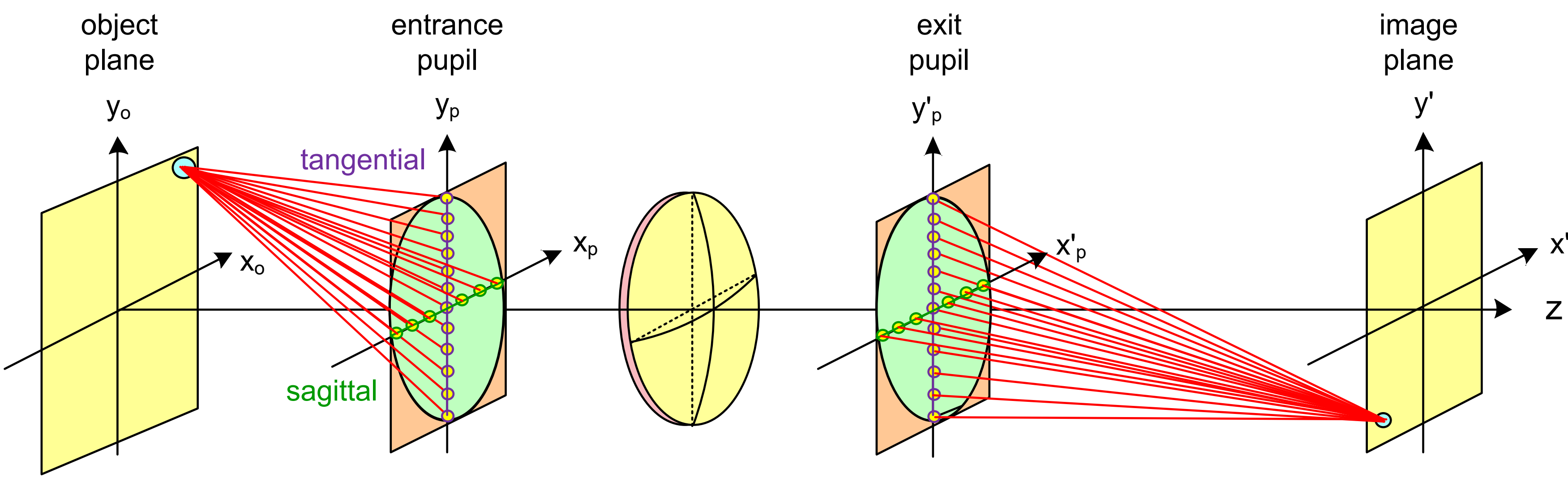
Special rays in 3D

- Meridional rays:
  in main cross section plane
- Sagittal rays:
  perpendicular to main cross section plane
- Coma rays:
  Going through field point and edge of pupil
- Oblique rays:
  without symmetry



Pupil sampling

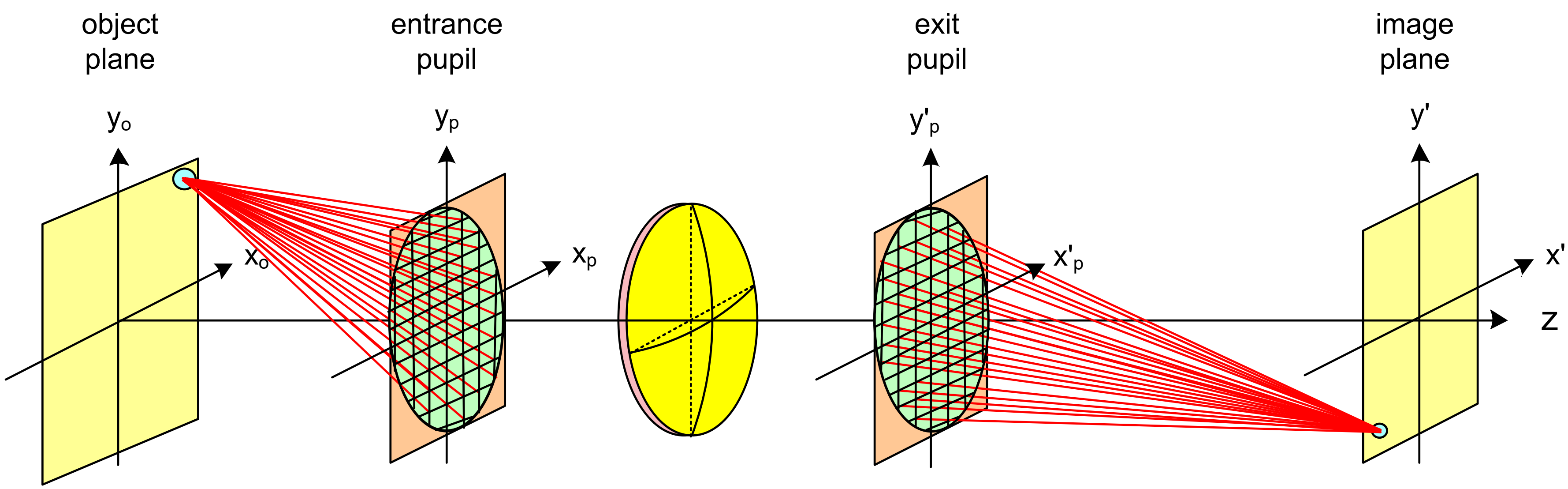
- Pupil sampling for calculation of transverse aberrations:
  all rays from one object point to all pupil points on x- and y-axis
- Two planes with 1-dimensional ray fans
- No complete information: no skew rays



Sampling of pupil area

- Pupil sampling in 3D for spot diagram:
  all rays from one object point through all pupil points in 2D

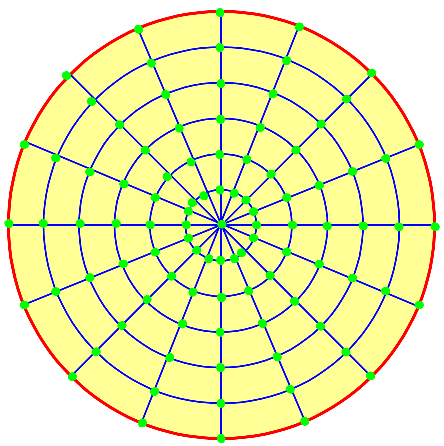
- Light cone completly filled with rays



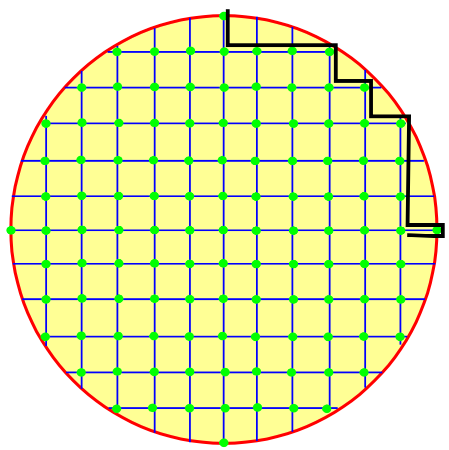
Pupil Sampling

- Criteria:
  1. iso energetic rays
  2. good boundary description
  3. good spatial resolution

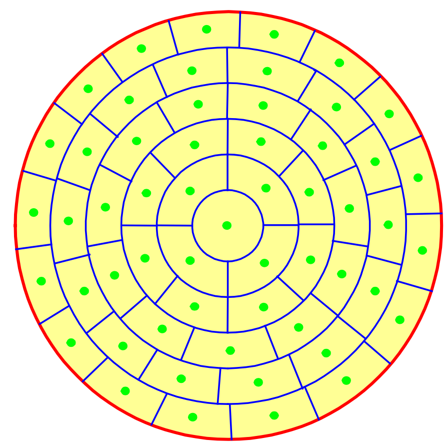
polar grid



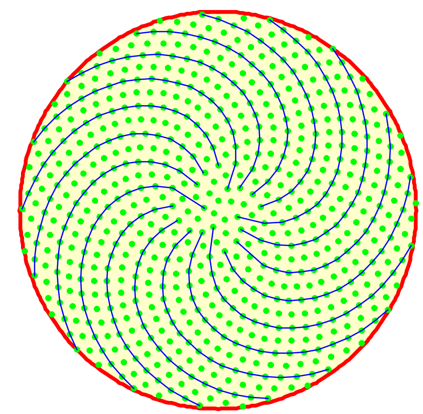
cartesian



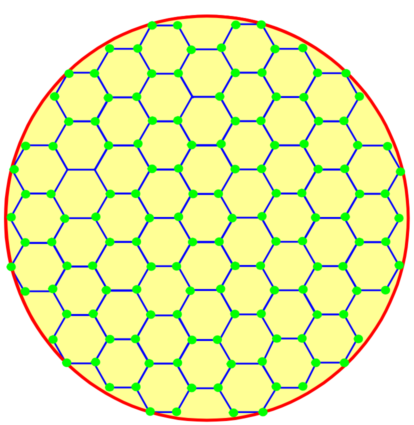
isoenergetic circular



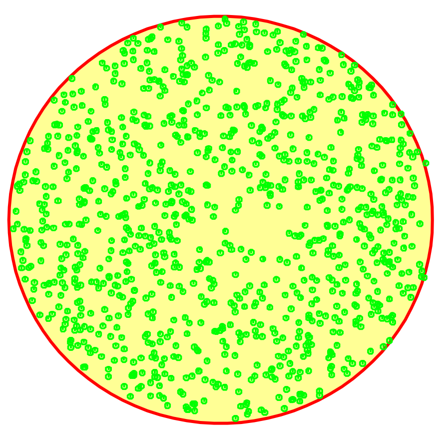
Fibonacci spirals



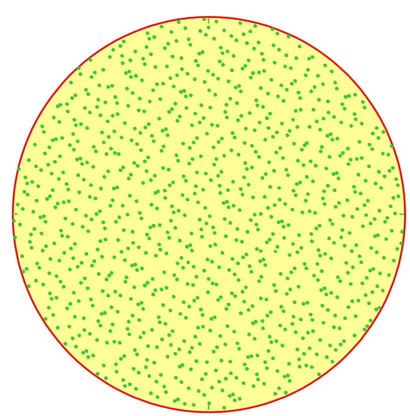
hexagonal



statistical



pseudo-statistical (Halton)



Artefacts of pupil sampling

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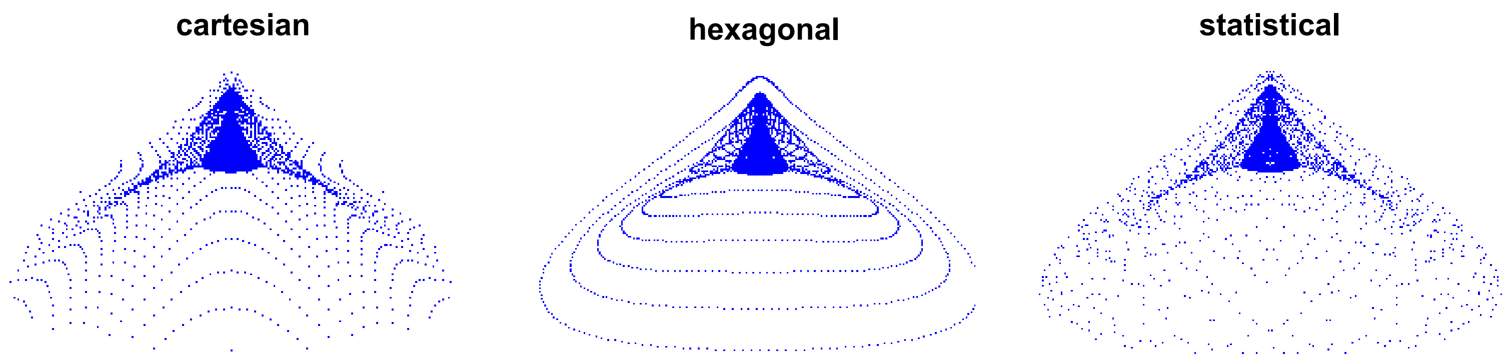
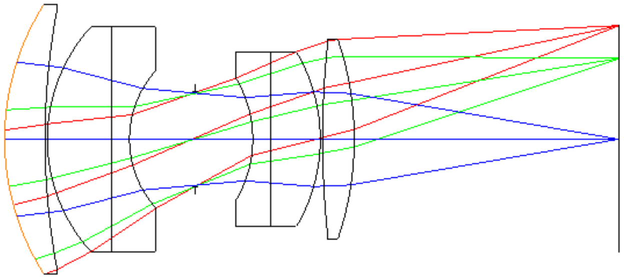
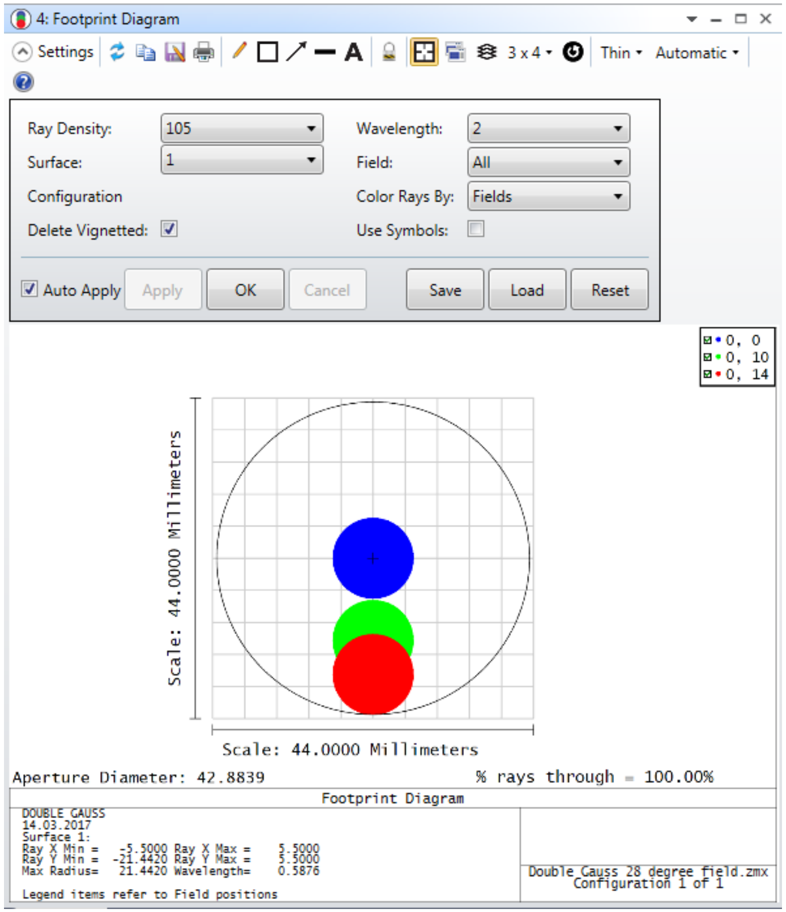
- Artefacts due to regular gridding of the pupil of the spot in the image plane
- In reality a smooth density of the spot is true
- The line structures are discretization effects of the sampling

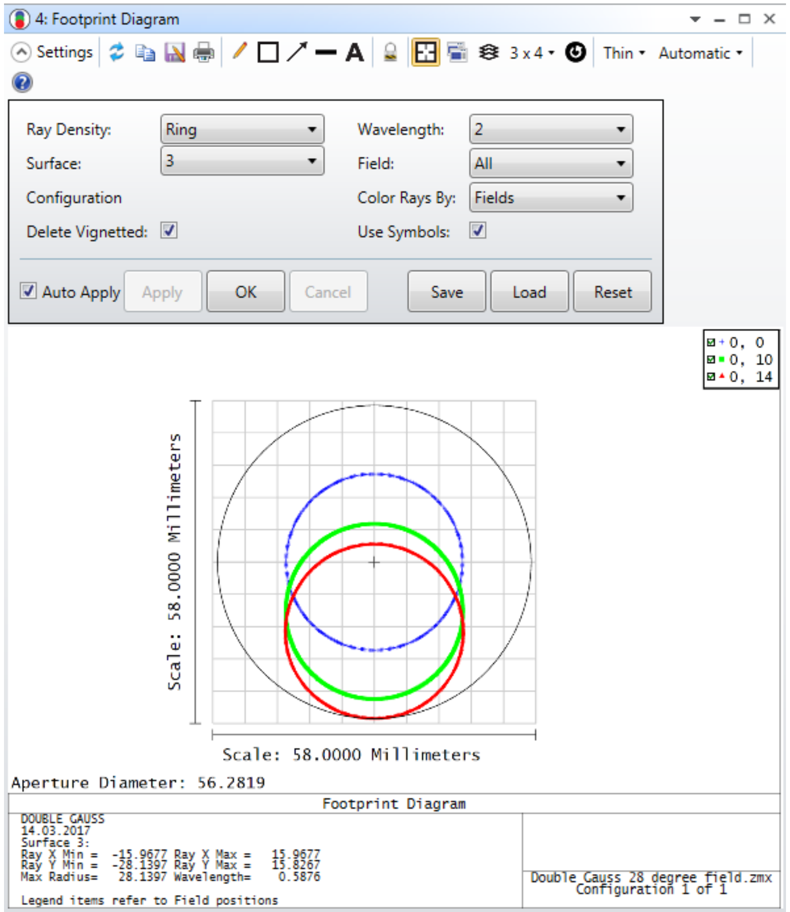


Footprints

- Ray bundle cross sections @ specific surfaces
- Equivalent to spot diagram







Exercise 1 Paraxial system layout

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a) Suppose a divergent ray bundle with numerical aperture of NA = 0.2 at the wavelength λ = 500 nm. Establish a first paraxial lens with a focal length to get a collimated beam with diameter 24 mm.

b) After a distance of 10 mm a second paraxial lens with focal length f2 = 30 mm focusses the ray. Behind the focal point a third paraxial lens should collimate the beam again for a diameter of 36 mm.

c) Now in a distance of 20 mm a focussing paraxial lens with focal length f = 100 is added. Finally a negative lens with f = -70 mm is added in an appropriate distance to change the numerical aperture in the image space to 0.05. Find the final image distance. What is the magnification of the system ?

Exercise 2 Singlet

Establish a single lens with the following data:

wavelength:	λ = 546.07 nm
object distance	100 mm
thickness of the lens, made of N-BK7	t = 8 mm
front radius of curvature	R1 = 45 mm
rear radius of curvature	R2 = -100 mm
numerical aperture in the object space	NA = 0.07
lens diameter	24 mm

a) Fix the final distance in the paraxial image plane. Create a layout plot

b) Calculate the spot diagram and the transverse ray aberrations.
What is the spot size ?
Is the system diffraction limited ?
What residual aberration is obtained ?
Are also higher order aberrations obtained ?
Determine the image sided numerical aperture by calculating the marginal ray.

c) Add an off axis field point with height y = 10 mm.
Fix the pupil of the system at the rear surface of the lens
Find the best plane for gathering the image. Is the distance increased or decreased ?
Calculate the layout and the spot diagram. What is the dominating aberration for the field point now ?