Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Lens Design I

Lecture 12: Correction II

2024-07-04

Yueqian Zhang

Preliminary Schedule - Lens Design I 2024

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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

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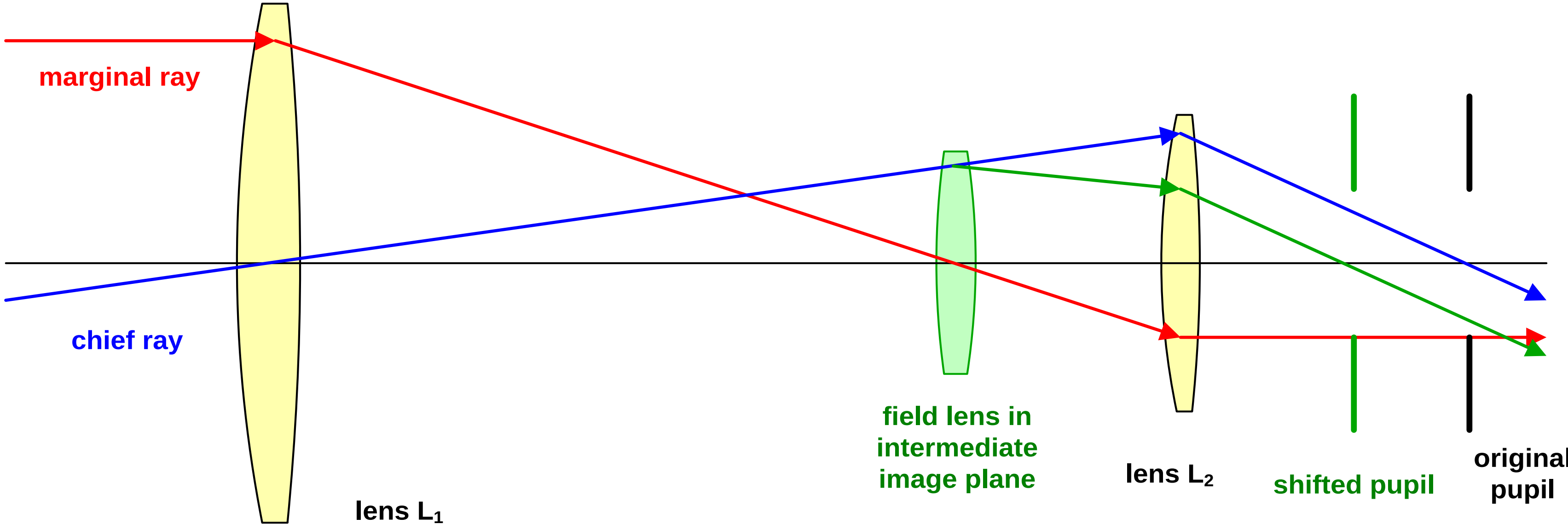
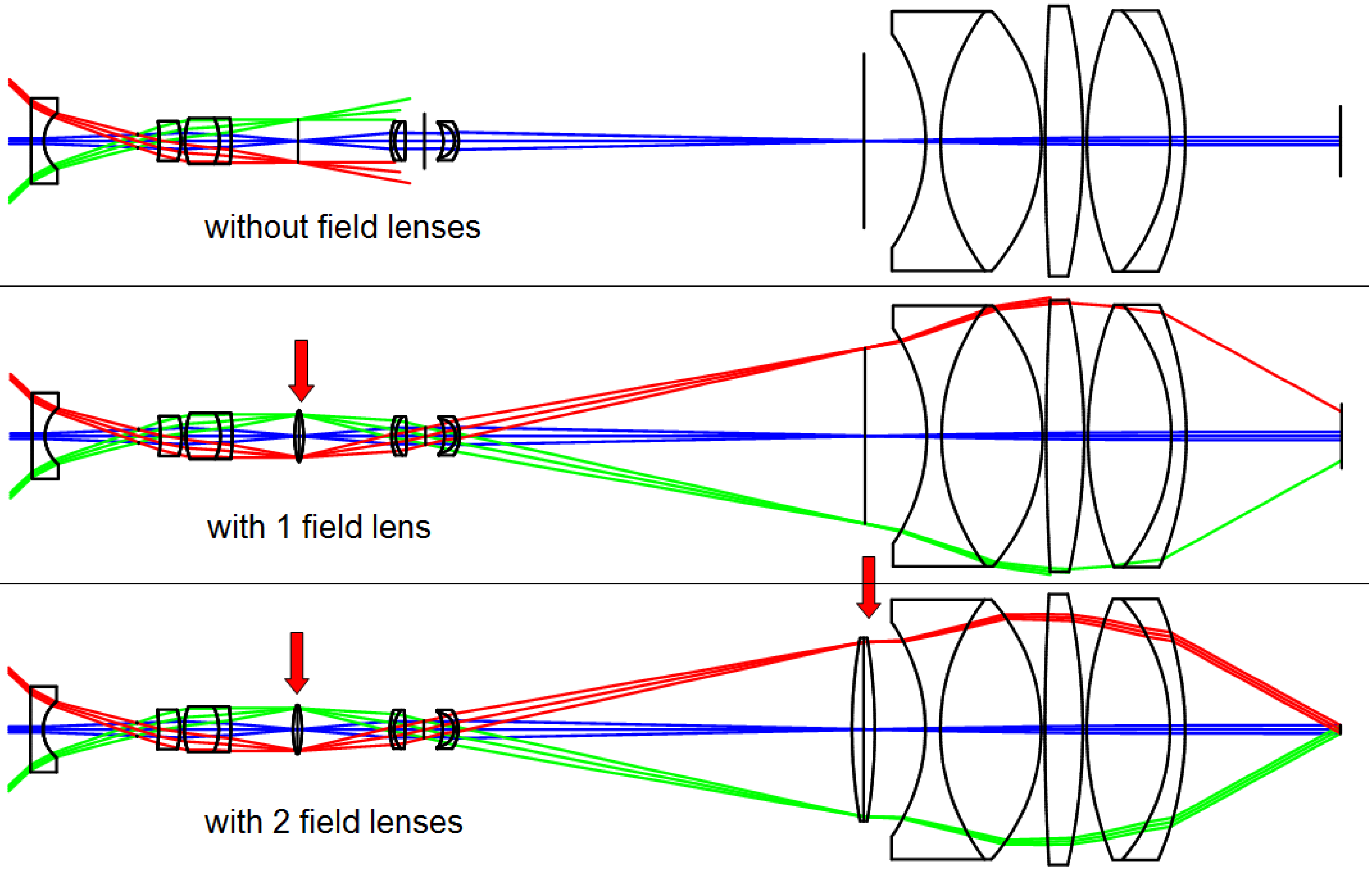
Field Lenses

- Field lens: in or near image planes
- Influences only the chief ray: pupil shifted
- Critical: conjugation to image plane, surface errors sharply seen



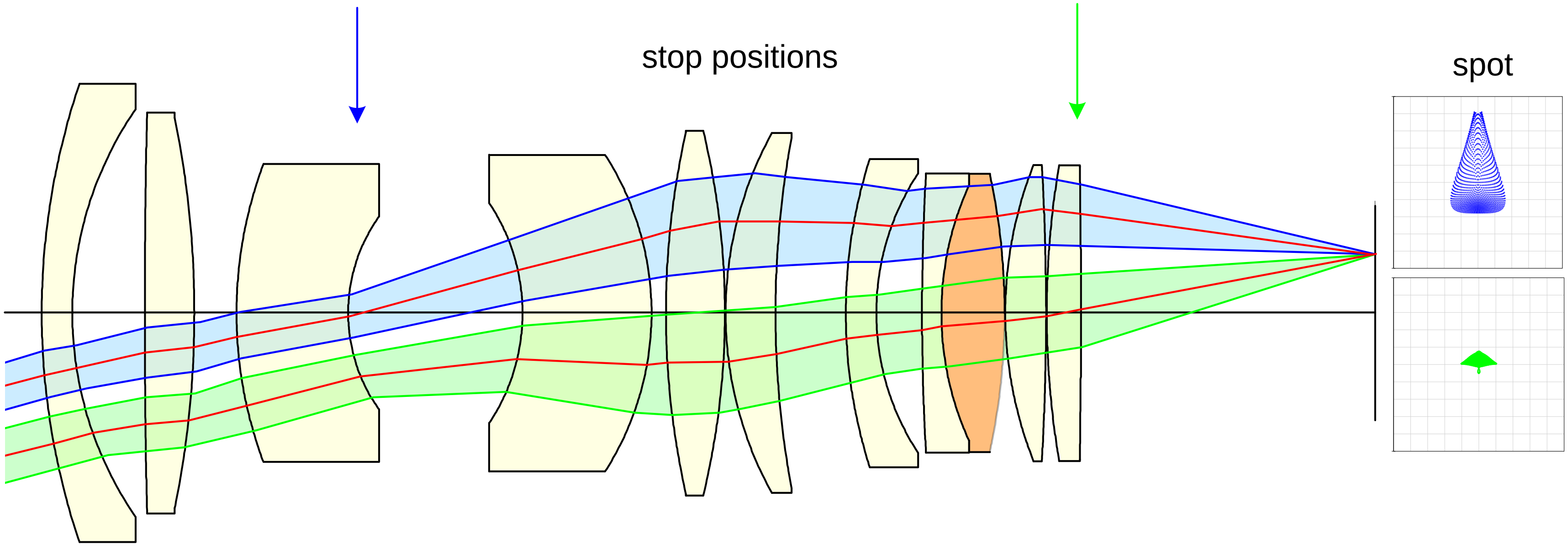
Field Lens im Endoscope



Ref : H. Zügge

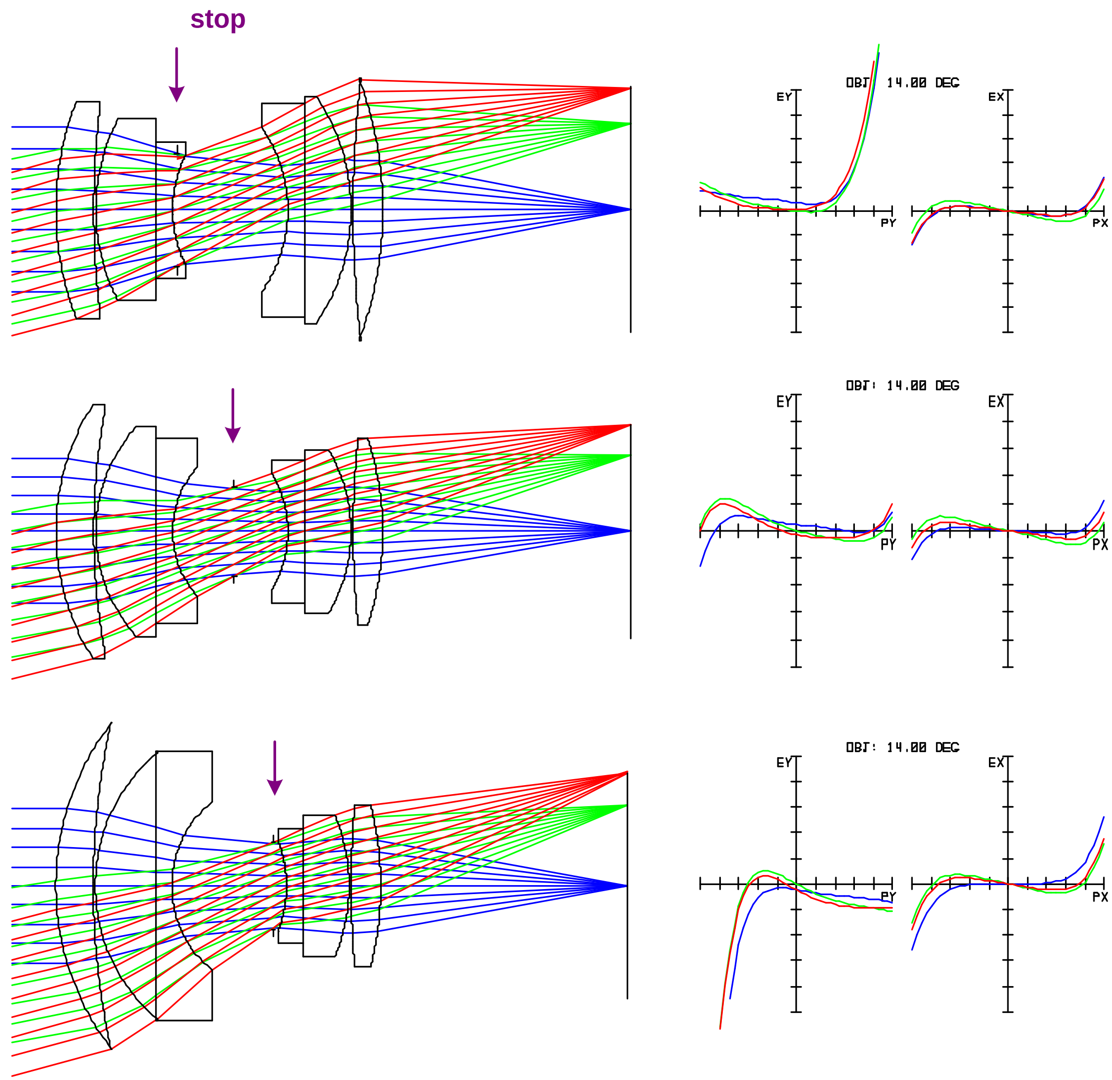
Influence of Stop Position on Performance

- Ray path of chief ray depends on stop position



Effect of Stop Position

- Example photographic lens
- Small axial shift of stop changes tranverse aberrations
- In particular coma is strongly influenced



Ref: H.Zügge

Telephoto Systems

- Combination of a positiv and a negative lens:
  Shift of the first principal plane in front of the system
- The intersection length is smaller than the focal length: reduction factor k
- Typical values: k = 0.6...0.9
- Focal lengths:

$$f_a = \frac{f' \cdot d}{f' \cdot (1-k) + d}$$

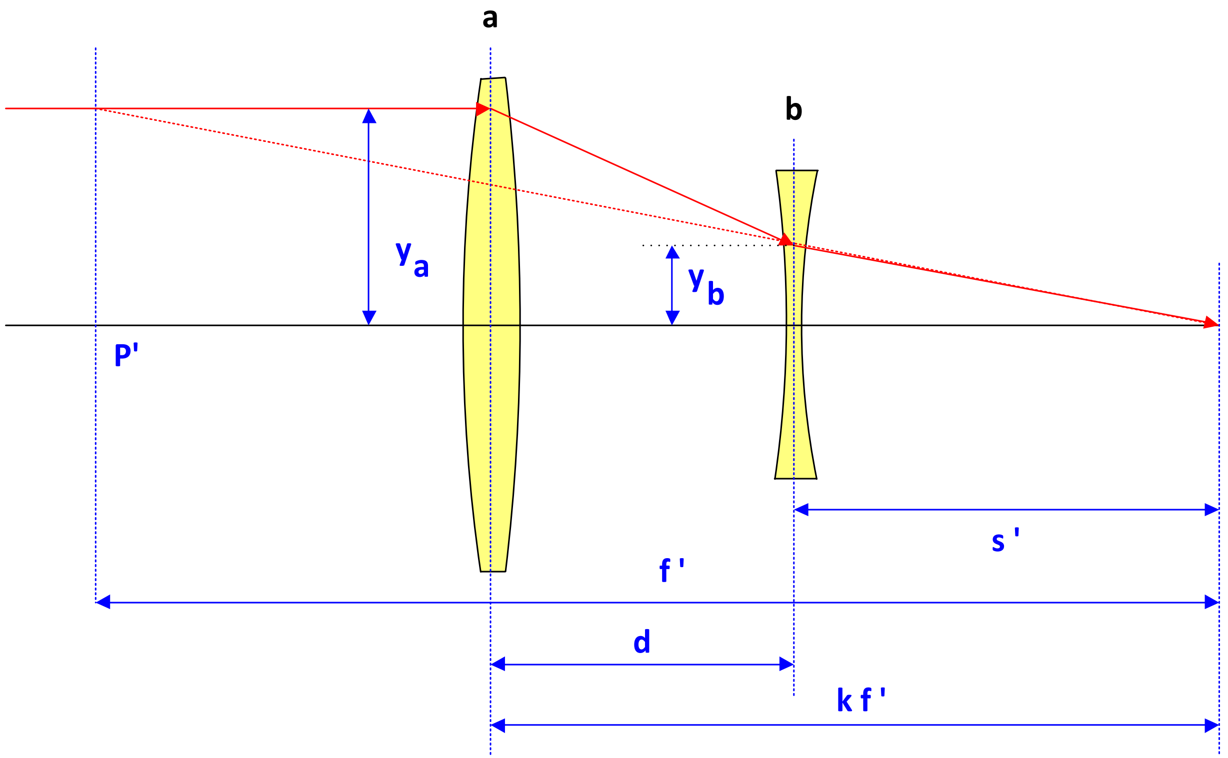
$$f_b = \frac{\left(f_a - d\right)\left(kf' - d\right)}{f_a - kf'}$$

- Overall length

$$L = k \cdot f'$$

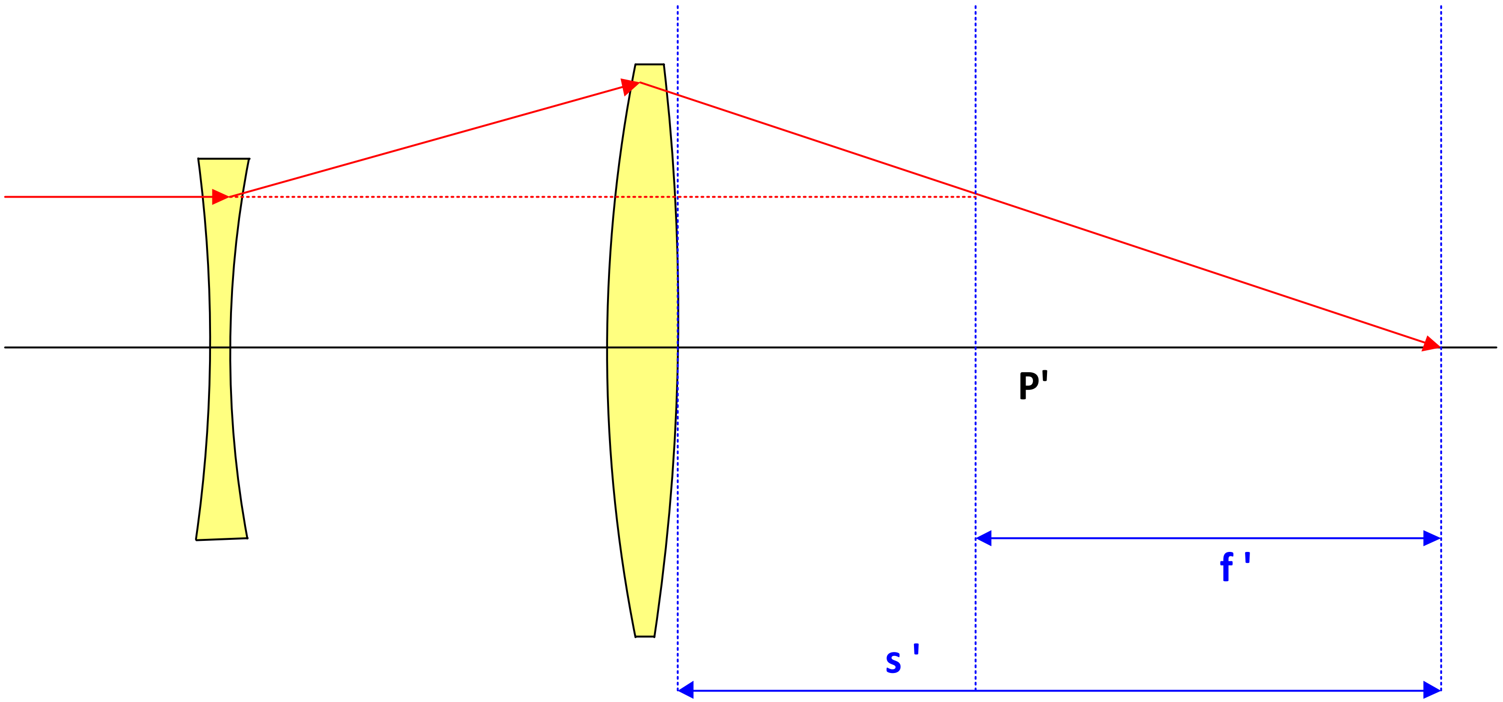
- Free intersection length

$$s_f = k \cdot f' - d$$



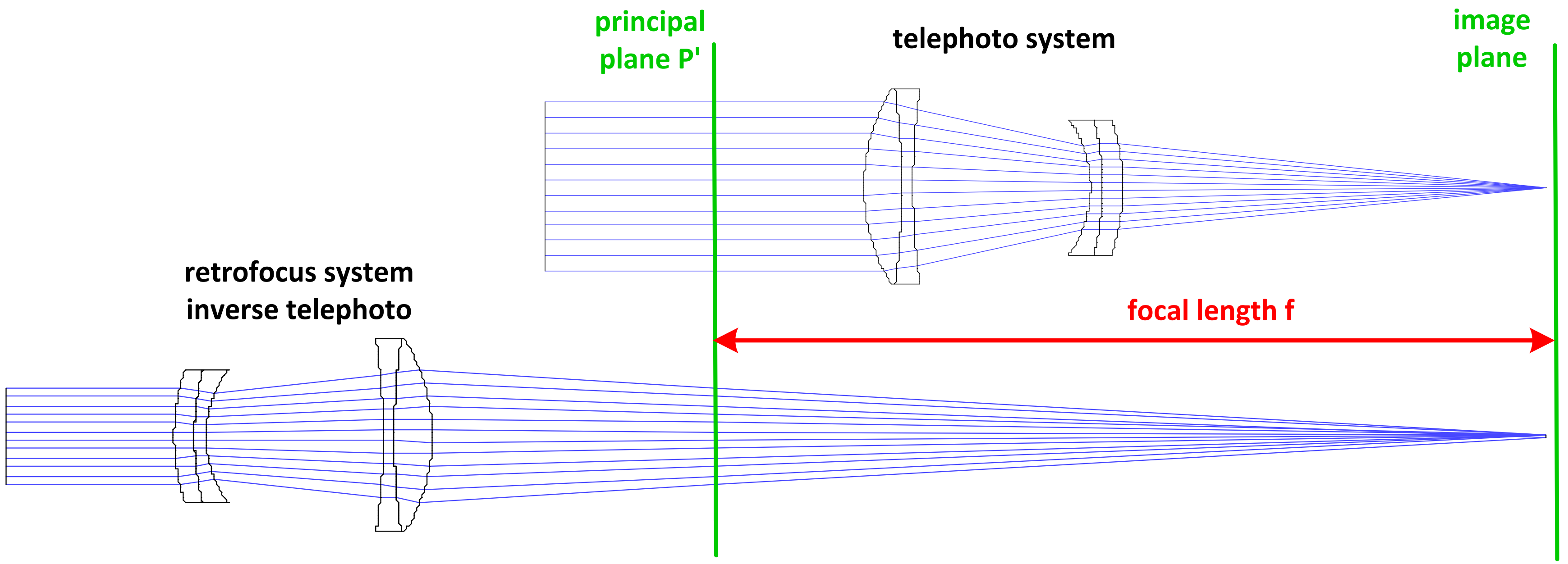
Retrofocal System

- Combination of a negative and a positive lens:
  Shift of the second principal plane behind the system
- The intersection length is larger than the focal length
- Application: systems for large free working distance
- Corresponds to an inverse telephoto system



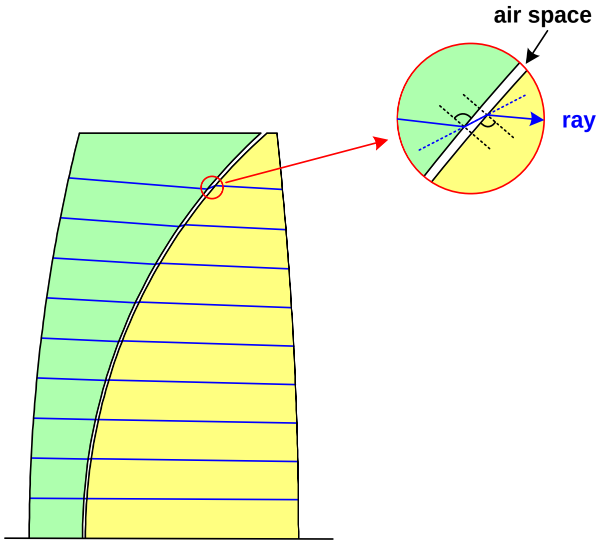
Telephoto and inverse Telephoto Principle

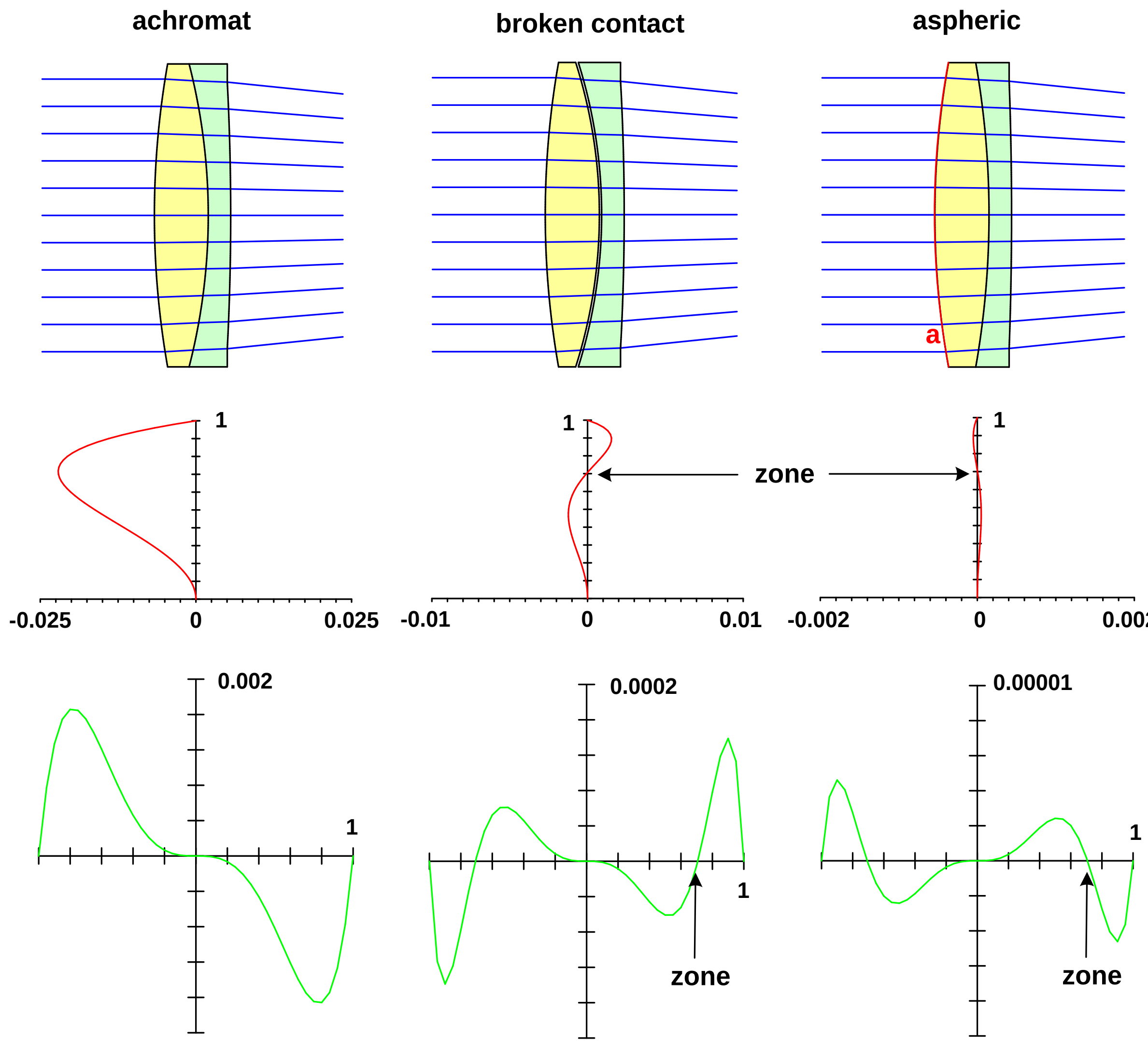
Retrofocus system results form a telephoto system by inversion



Higher Order Aberrations: Achromate, Aspheres

- Splitted achromate





- Aspherical surface

Ref : H. Zügge

Merte Surface

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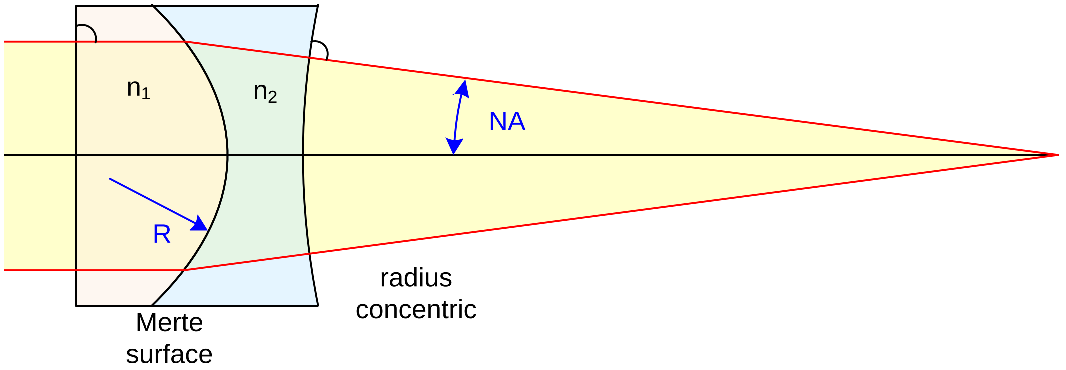
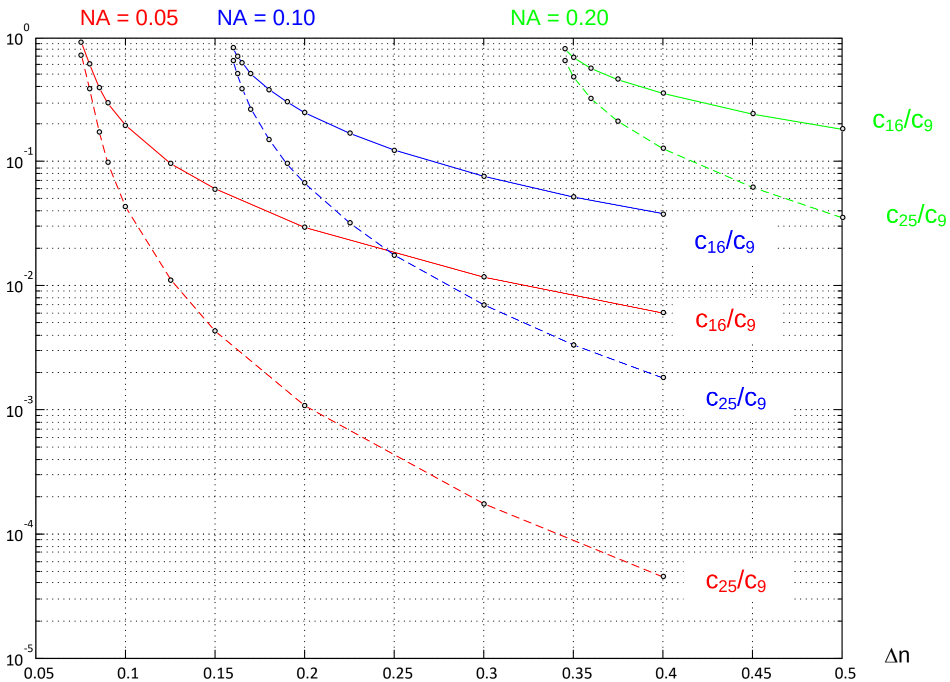
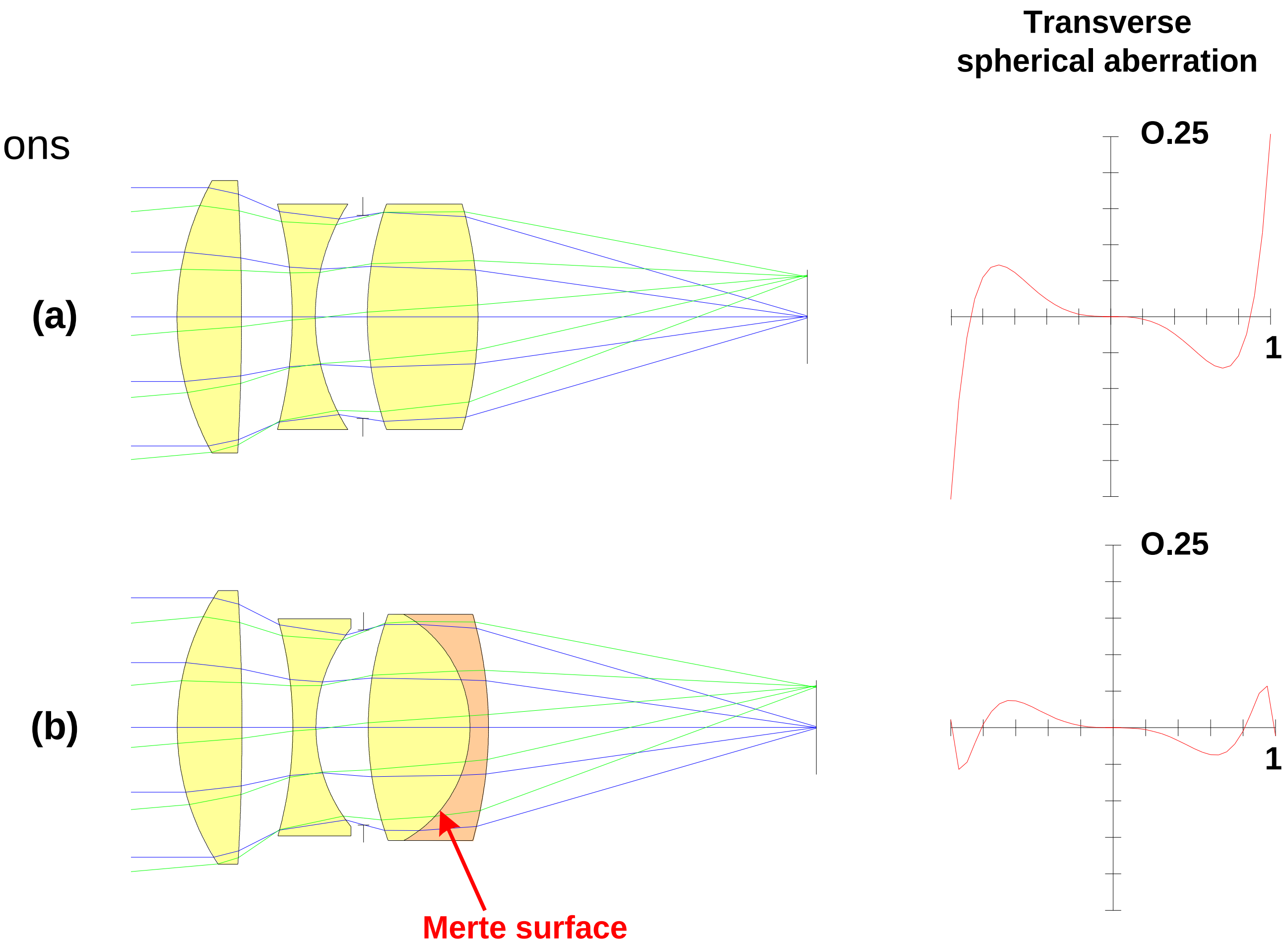
- Small difference in refractive index
- Growing higher order contributions





Higher Order Aberrations: Merte Surface

- Merte surface:
  - low index step
  - strong bending
  - mainly higher aberrations generated

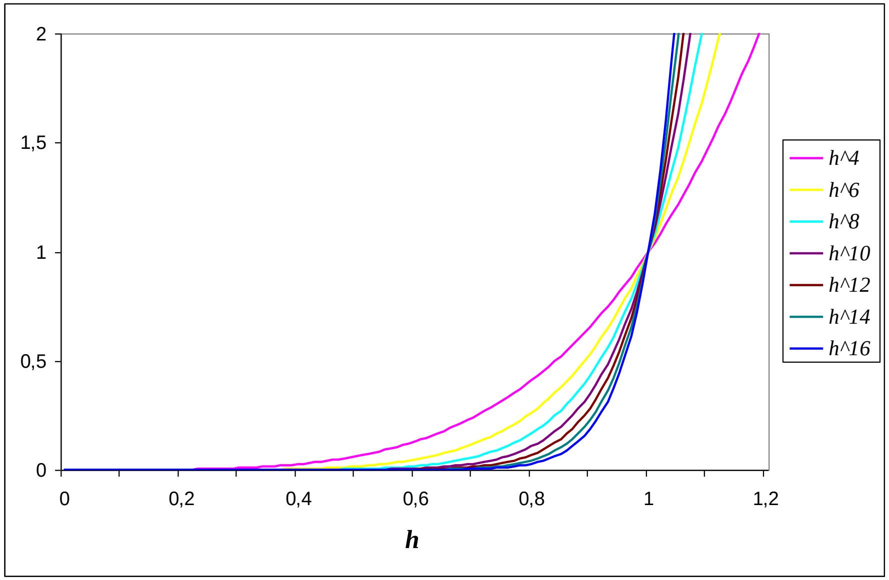


From : H. Zügge

- Basic form of a conic section superimposed by a Taylor expansion of z

$$z(h) = \frac{\rho h^2}{1+\sqrt{1-(1+c)\rho^2 h^2}} + \sum_{m=0}^{M} a_m h^{2m+4}$$

h ... Radial distance to optical axis
ρ ... Curvature
c ... Conic constant
a_m ... Apherical coefficients



Ref: K. Uhlendorf

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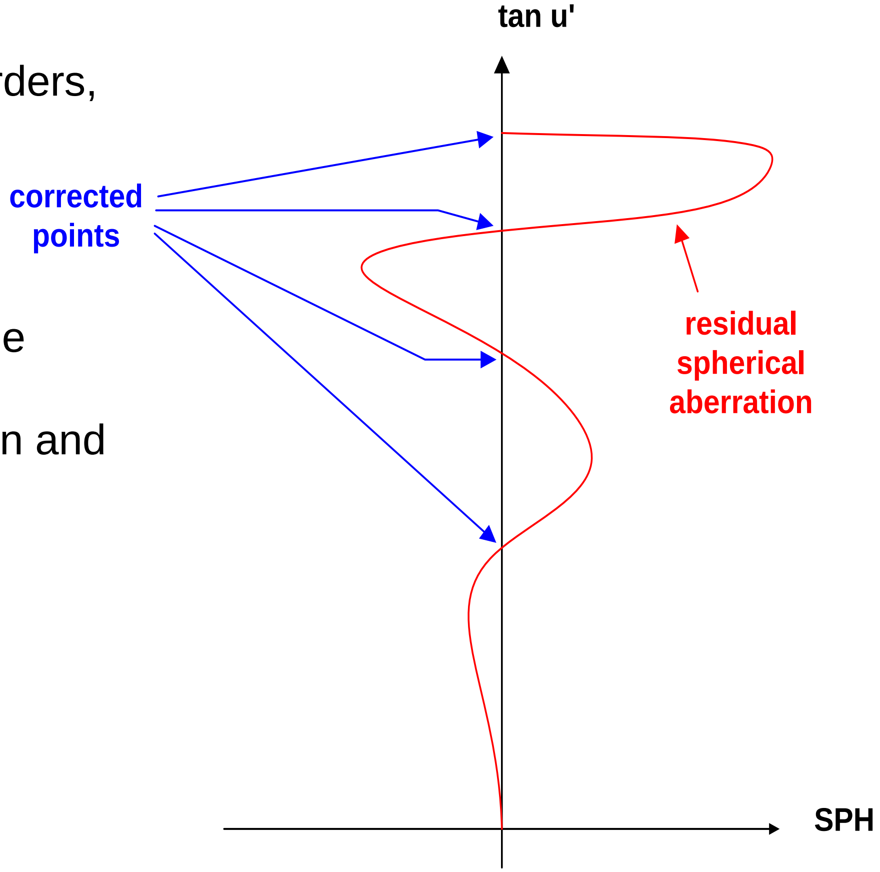
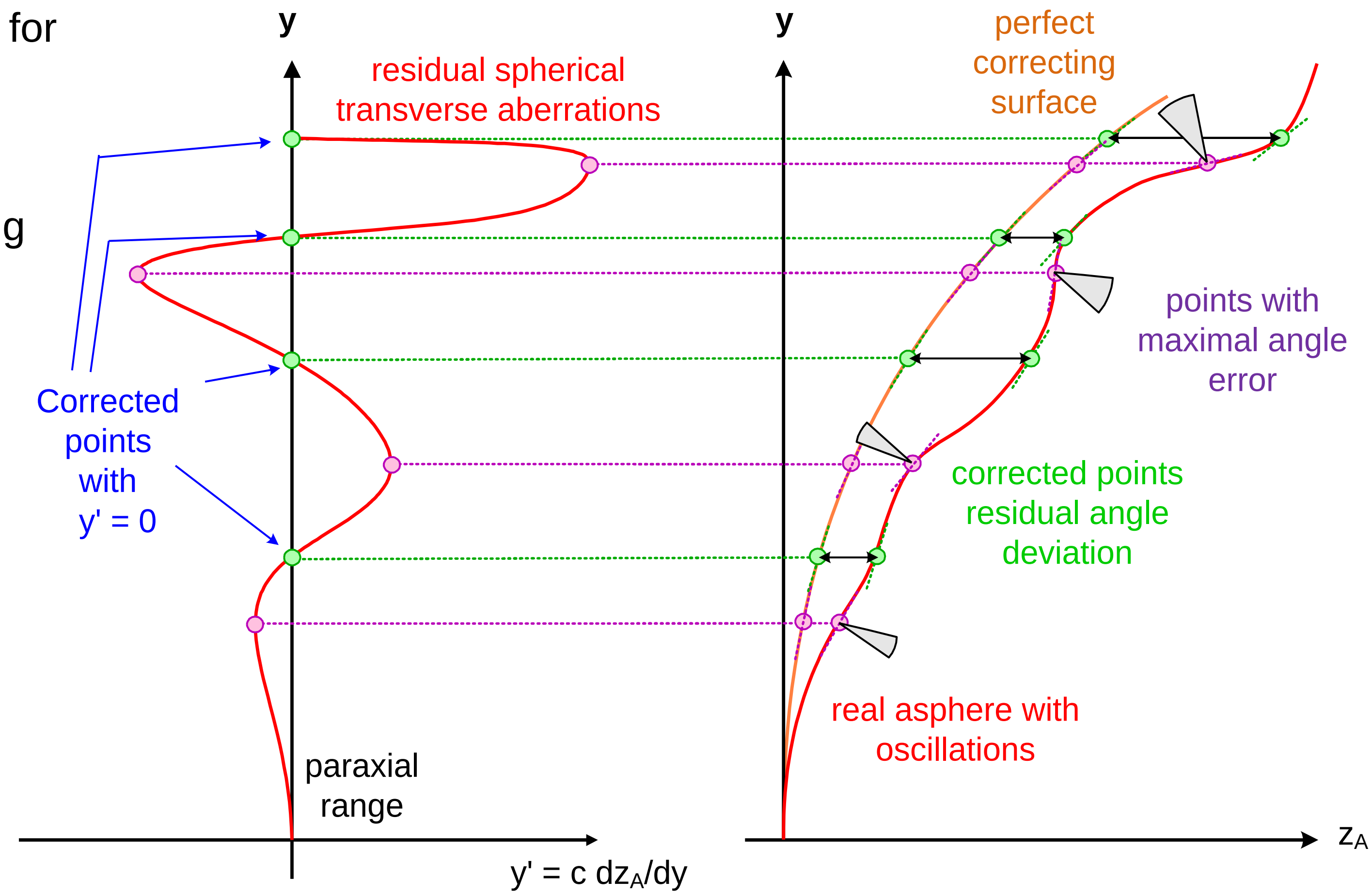
Aspherical Surfaces

- Additional degrees of freedom for correction
- Exact correction of spherical aberration for a finite number of aperture rays
- Strong asphere: many coefficients with high orders, large oscillative residual deviations in zones
- Location of aspherical surfaces:
  1. spherical aberration: near pupil
  2. distortion and astigmatism: near image plane
- Use of more than 1 asphere: critical, interaction and correlation of higher oders



Aspheres: Correction of Higher Order

- Correction at discrete sampling
- Large deviations between sampling points
- Larger oscillations for higher orders
- Better description: slope, defines ray bending



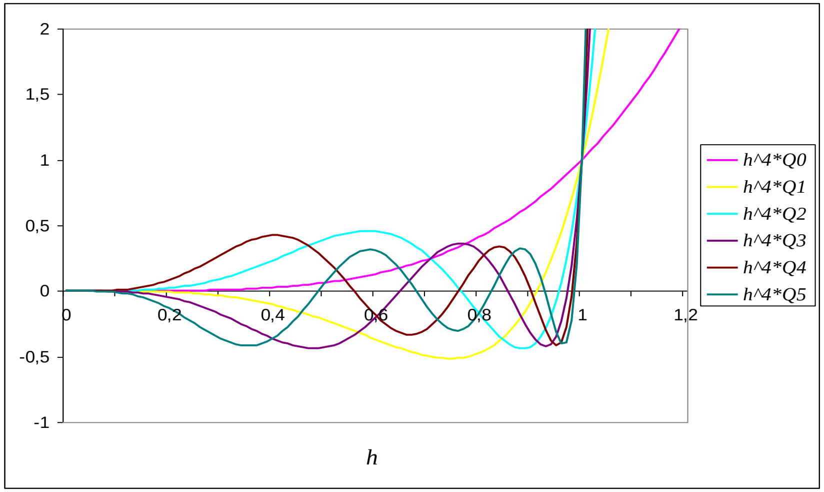
Polynomial Aspherical Surface
Forbes Aspheres - Q_{con}

- New orthogonalization and normalization using Jacobi-polynomials Q_m

$$z(h) = \frac{\rho h^2}{1+\sqrt{1-(1+c)\rho^2 h^2}} + (h/h_{max})^4 \sum_{m=0}^{M} a_m Q_m\left((h/h_{max})^2\right)$$

requires normalization radius h_{max}

(1:1 conversion to standard aspheres possible)



- Mean square slope

$$\sum_{m=0}^{M} a_m / (m+5)$$

Ref: K. Uhlendorf

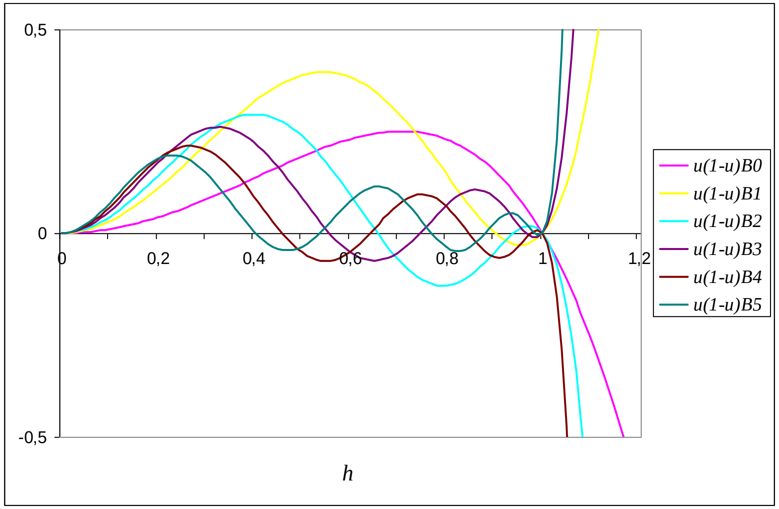
- Limit gradients by special choice of the scalar product

$$z(h) = \frac{\rho_0 h^2}{1+\sqrt{1-\rho_0^2 h^2}} + \frac{u(1-u)}{\sqrt{1-\rho_0^2 h^2}} \sum_{m=0}^{M} a_m B_m(u) \quad \text{mit} \quad u := (h/h_{\max})^2$$

(1:1 conversion to standard aspheres not possible)

- Mean square slope

$$(1/h_{\max})^2 \sum_{m=0}^{M} a_m{}^2$$

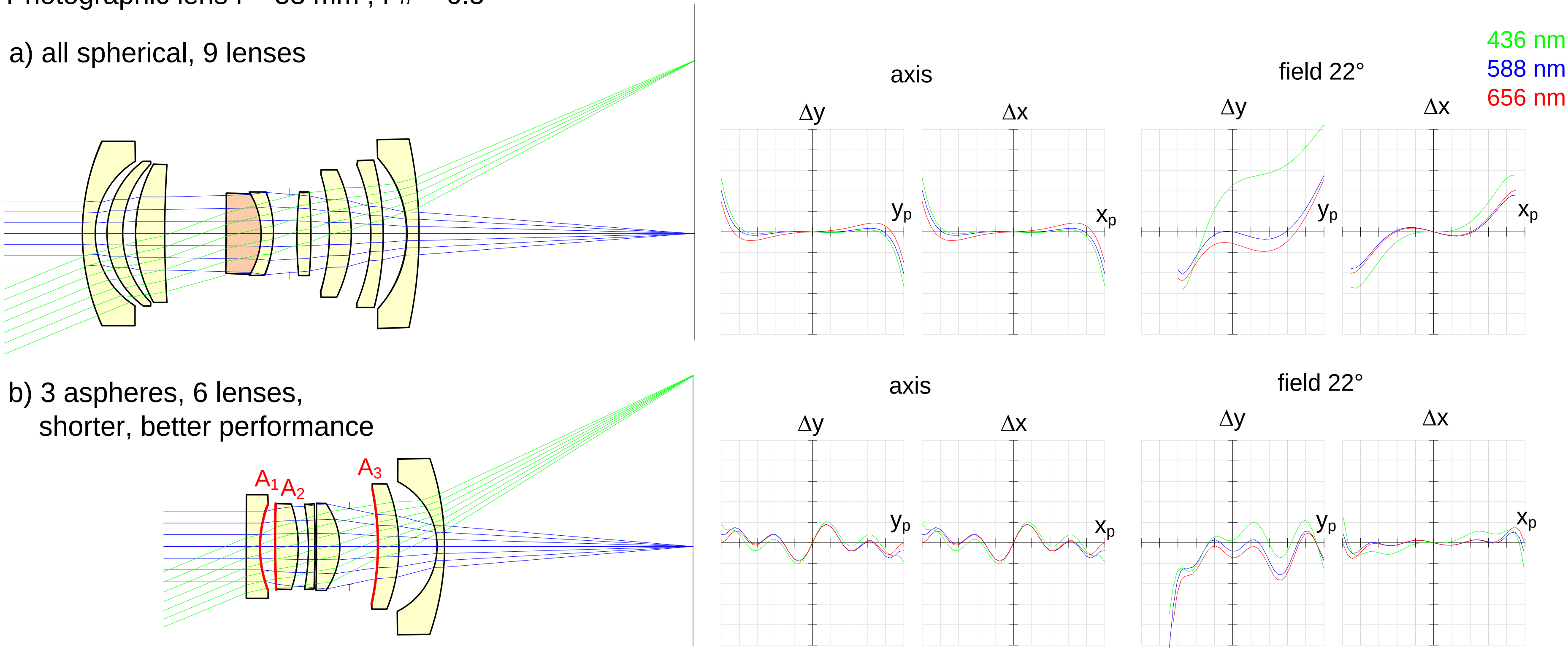


Ref: K. Uhlendorf

Reducing the Number of Lenses with Aspheres

- Example photographic zoom lens
- Equivalent performance
- 9 lenses reduced to 6 lenses
- Overall length reduced

Photographic lens f = 53 mm , F# = 6.5



Ref: H. Zügge

Lithographic Projection: Improvement by Aspheres

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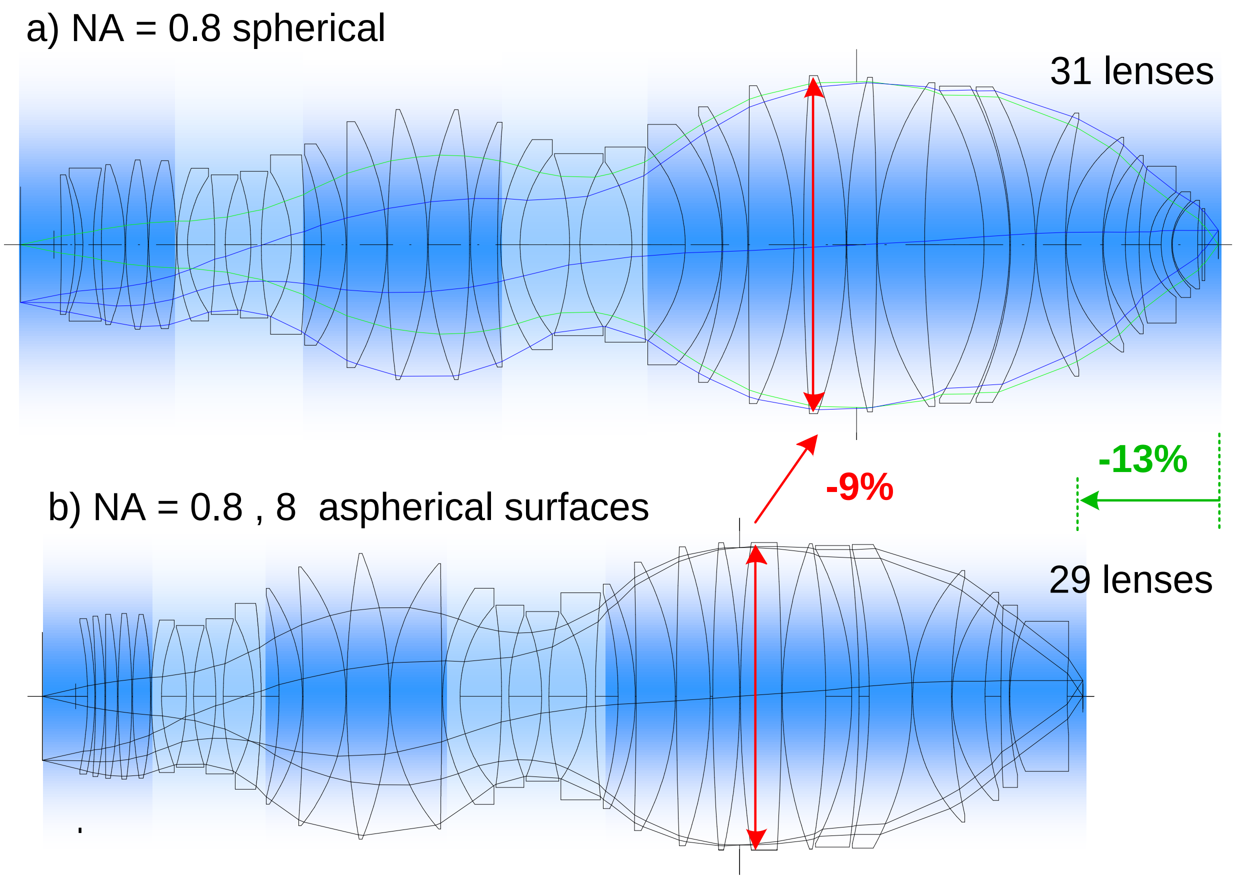
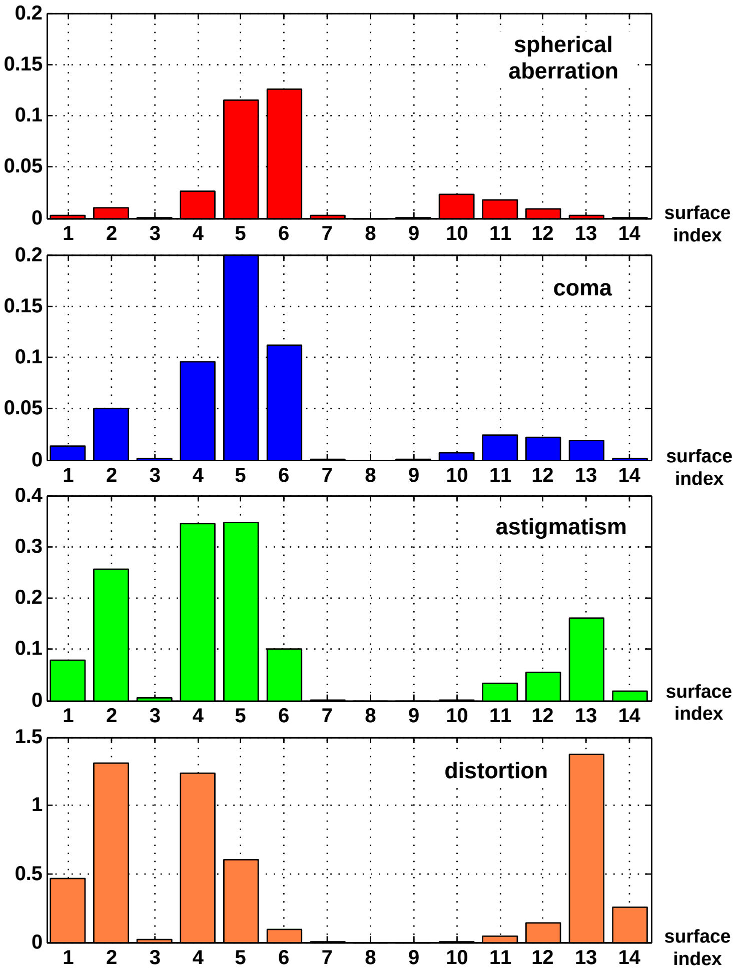
- Considerable reduction of length and diameter by aspherical surfaces
- Performance equivalent
- 2 lenses removable

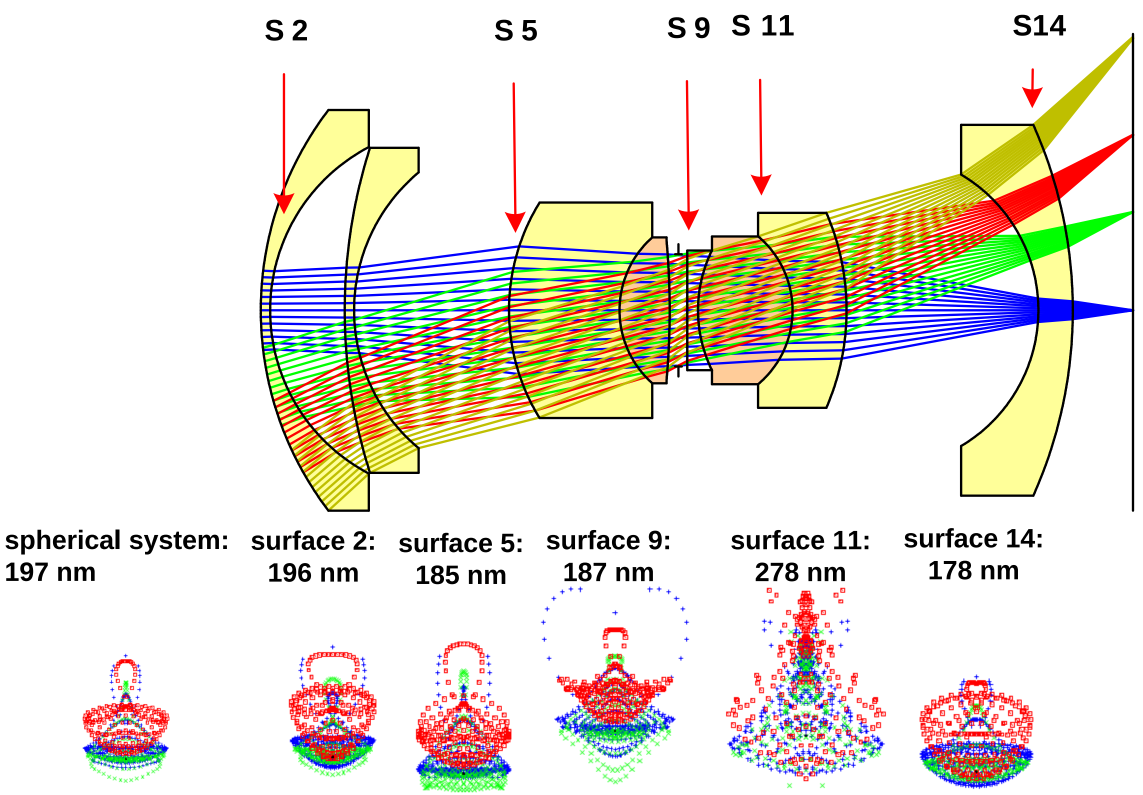


Ref: W. Ulrich

Aspherization of a Camera Lens

- Selection of one aspherical surface in a photographic lens





Freeform Systems: Surface Representations

- Extended polynomials
  classical non-orthogonal monomial representation
- Zernike surface
  Only useful for circular pupils and low orders
- Splines
  Localized description, hard to optimize, good for manufacturing characterization
- Generalized Forbes polynomials
  Promising new approach, two types, strong relation to tolerancing
- Radial basis functions
  Non-orthogonal local description approach, good for local effect description
- Wavelets
  Not preferred for smooth surfaces, only feasible for tolerancing
- Fourier representation
  Classical description without assumptions, but not adapted to aberrations
- Smooth vs segmented, facetted, steps, non-Fermat surfaces
  Real world is still more complicated

Freeform Systems: Equations of Description

- Extended polynomials in x,y:

$$z(x,y)=\frac{c_x x^2+c_y y^2}{1+\sqrt{1-(1-\kappa_x)c_x^2x^2-(1-\kappa_x)c_x^2x^2}}+\cdot\sum_{n,m=2}a_{n,m}\cdot x^n y^m$$

- Zernike expansion

$$z(x,y)=\frac{c_x x^2+c_y y^2}{1+\sqrt{1-(1-\kappa_x)c_x^2x^2-(1-\kappa_x)c_x^2x^2}}+\cdot\sum_{j=0}c_j\cdot Z_j(x,y)$$

- Extended Forbes asphere
- Expansion in other orthogonal polynomial systems: Legendre, Chebychev, ...

$$z(x,y)=\frac{cr^2}{1+\sqrt{1-c^2r^2}}+\frac{\frac{r^2}{a^2}\cdot\left(1-\frac{r^2}{a^2}\right)}{\sqrt{1-c^2r^2}}\cdot\sum_{n=0}a_n^0Q_n^0\left(\frac{r^2}{a^2}\right)$$

$$+\sum_{m=1}\left(\frac{r}{a}\right)^m\sum_{n=0}\left[a_n^m\cos(m\theta)+b_n^m\sin(m\theta)\right]\cdot Q_n^m\left(\frac{r^2}{a^2}\right)$$

- Fourier expansion

$$z(x,y)=\frac{c_x x^2+c_y y^2}{1+\sqrt{1-(1+\kappa_x)c_x^2x^2-(1+\kappa_y)c_y^2y^2}}+\sum_{n,m}B_{nm}\cdot\mathrm{Re}\left[e^{-ik_{xn}x-ik_{ym}y}\right]$$

- Expansion into non-orthogonal local shifted Gaussian functions (RBF)

$$z(x,y)=\frac{c_x x^2+c_y y^2}{1+\sqrt{1-(1+\kappa_x)c_x^2x^2-(1+\kappa_y)c_y^2y^2}}+\sum_{n,m}a_{nm}\cdot e^{-\left(\frac{x-x_n}{w_x}\right)^2-\left(\frac{y-y_n}{w_y}\right)^2}$$

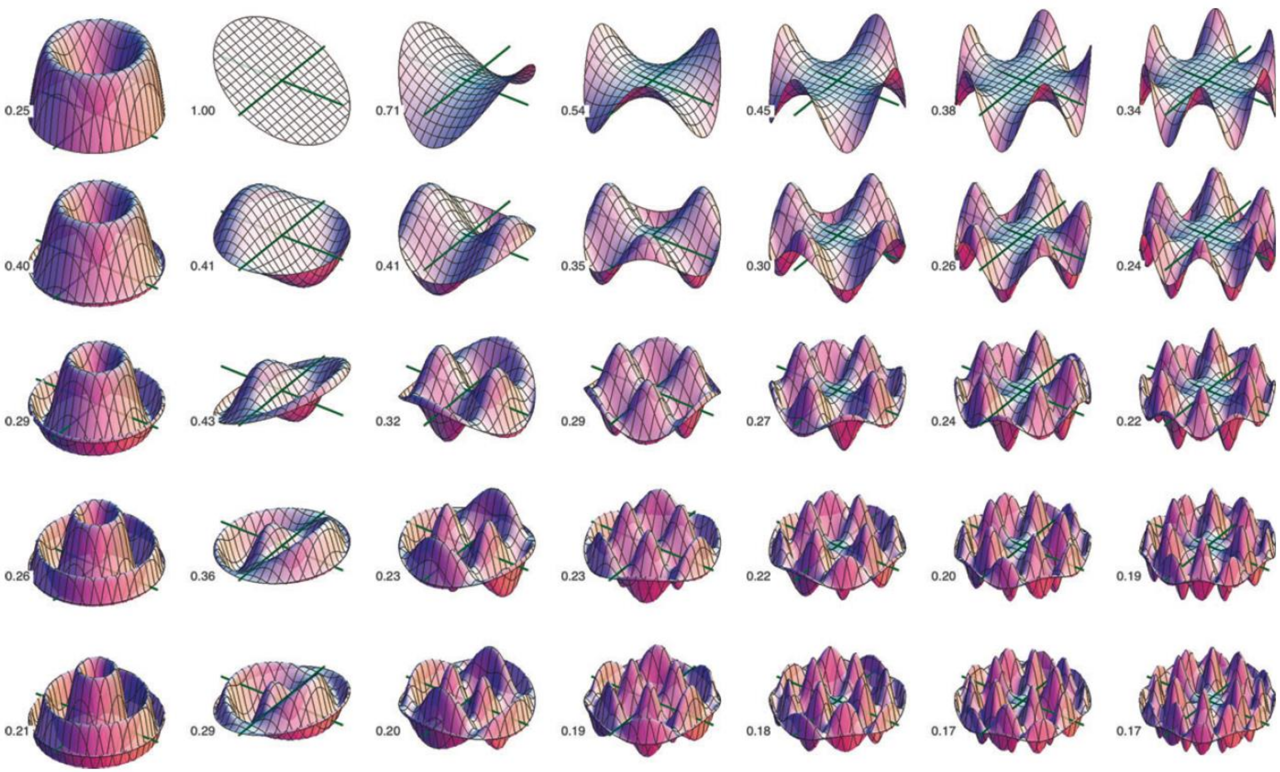
- Cubic spline, locally in patch j,k defined as polynomials of order 3

$$z_{j,k}(x,y)=\sum_{m=0}^{3}\sum_{n=0}^{3}a_{jkmn}\cdot\left(x-x_j\right)^m\cdot\left(y-y_k\right)^n$$

Freeform Systems: Forbes Surfaces

- Generalized approach for orthogonal surface decomposition
- Slope orthogonality is guaranteed and is related to tolerancing

$$z(x,y)=\frac{cr^2}{1+\sqrt{1-c^2r^2}}+\frac{\frac{r^2}{a^2}\cdot\left(1-\frac{r^2}{a^2}\right)}{\sqrt{1-c^2r^2}}\cdot\sum_{n=0}a_n^0Q_n^0\left(\frac{r^2}{a^2}\right)$$
$$+\sum_{m=1}\left(\frac{r}{a}\right)^m\sum_{n=0}\left[a_n^m\cos(m\theta)+b_n^m\sin(m\theta)\right]\cdot Q_n^m\left(\frac{r^2}{a^2}\right)$$



- Ref: C.Menke/G.Forbes, AOT 2(2013)p.97

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Freeform Systems: Exact Tailoring

- History:
  - exact solutions of Fermat-priciple for one wavelength and only a few field points corresponding to the number of surfaces
  - development of algorithms for illumination tailoring
  - mostly methods are applicable for illumination and imaging
- Dimension:
  - 2D is much easier / 3D is complicated and often not unique
- SMS-method of Minano
  - construction of the surfaces ray by ray with simple procedure
  - approved method in illumination and imaging
- Ries tailoring
  - method used since longer time
  - exact algorithm not known
- Oliker-Method for illumination
  approximation of smooth surface by sequence of parabolic arcs
- Reality:
  - due to finite size of surcse sna dbroadband applications tailored methods are only useful for finding a good starting system for optimization

Freeform Systems: Optimization

- Optimization of systems with freeform surfaces:
  - huge number of degrees of freedom
  - large differences in convergence according to surface representation
  - local vs global influence functions
  - definition of performance and formulation of merit function is complicated and cumbersome
- Classical system matrix for local defined splines is ill conditioned
- Starting systems:
  - still more important as in conventional optics
  - only a few well known systems published
  - larger archive for starting systems not available until now
  - own experience usually is poor
- Best location of FFF surfaces inside the system:
  - still more important as in the case of circular symmetric aspheres
  - no criteria known until now

Freeform Systems: Applications

- General purpose:
  - freeform surfaces are useful for compact systems with small size
  - due to high performance requirements in imaging systems and limited technological accuracy most of the applications are in illumination systems
  - mirror systems are developed first in astronomical systems with complicated symmetry-free geometry to avoid central obscuration

- HMD
  Head mounted device with extreme size constraints

- HUD
  Head up display, only few surfaces allowed

- Schiefspiegler
  - astronomical systems without central obscuration
  - EUV mirror systems for next generation lithography systems

- Illumination systems
  Various applications, smooth and segmented

Astigmatism of Oblique Mirrors

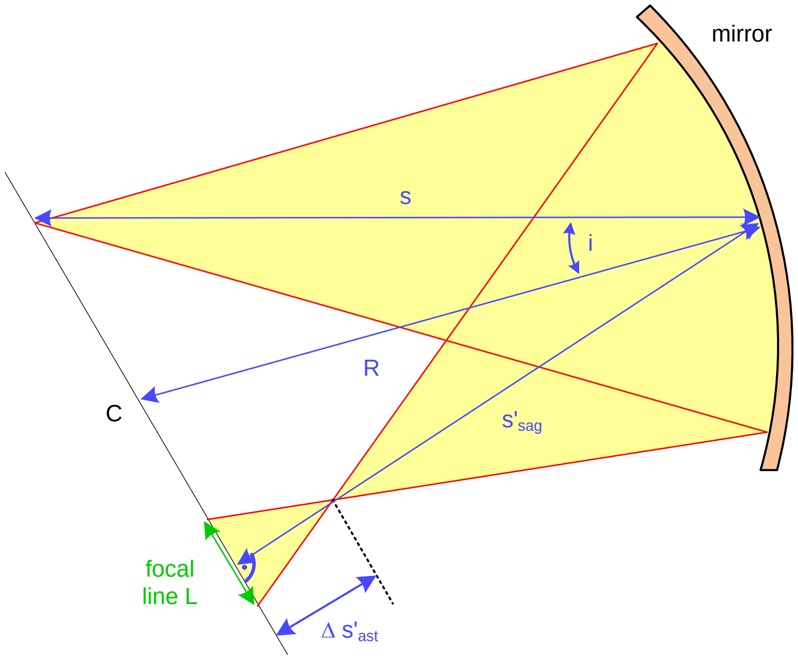
- Mirror with finite incidence angle:
  effective focal lengths

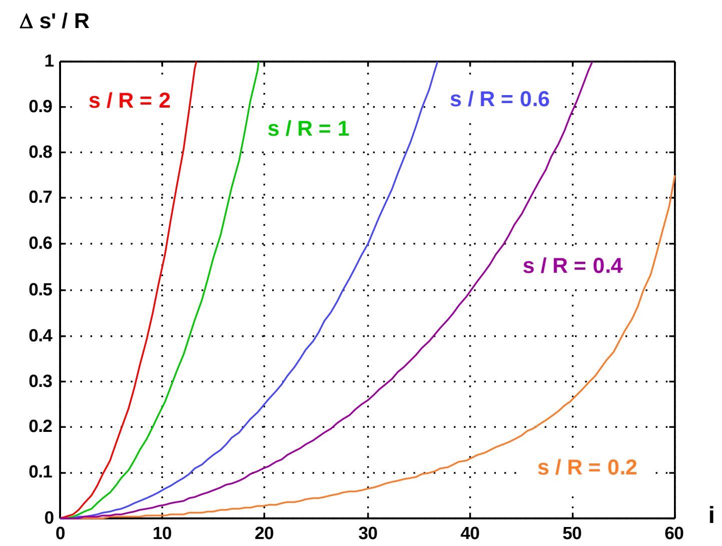
$$f_{\tan} = \frac{R \cdot \cos i}{2} \qquad f_{sag} = \frac{R}{2\cos i}$$

- Mirror introduces astigmatism

$$\Delta s'_{ast} = \frac{s^2 \cdot R \cdot \sin^2 i}{2\cos i \cdot \left(s - \frac{R\cos i}{2} \right) \cdot \left(s - \frac{R}{2\cos i} \right)}$$

- Parametric behavior of scales astigmatism

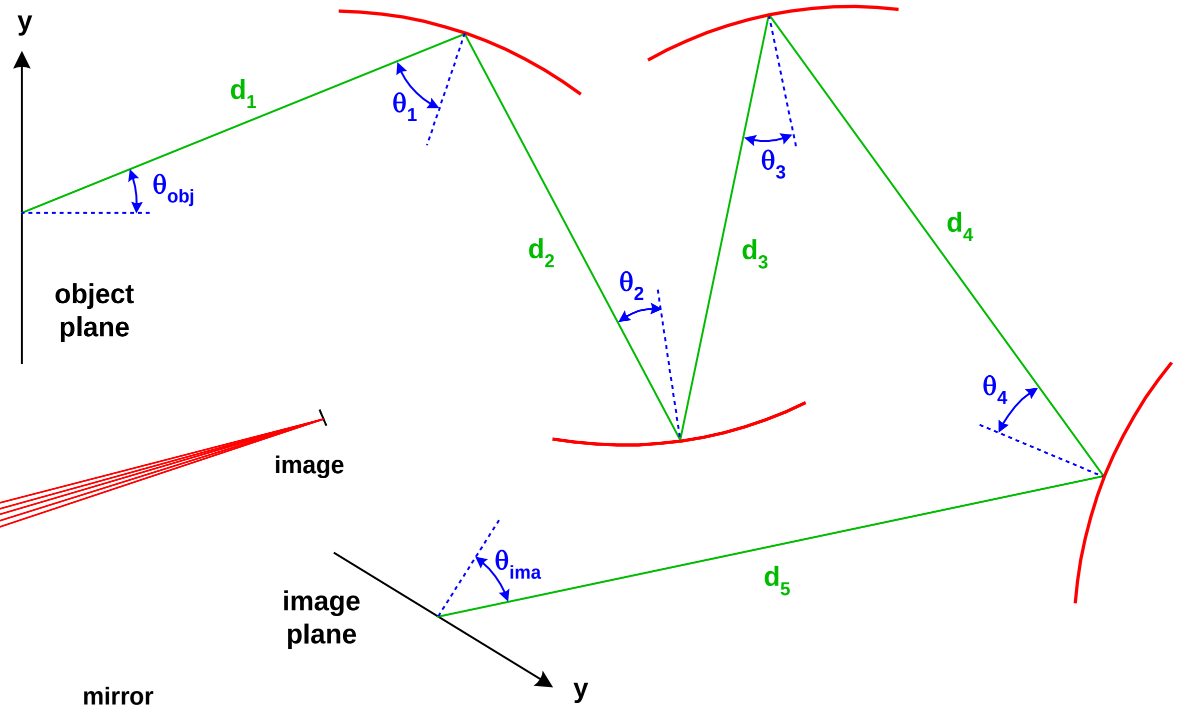


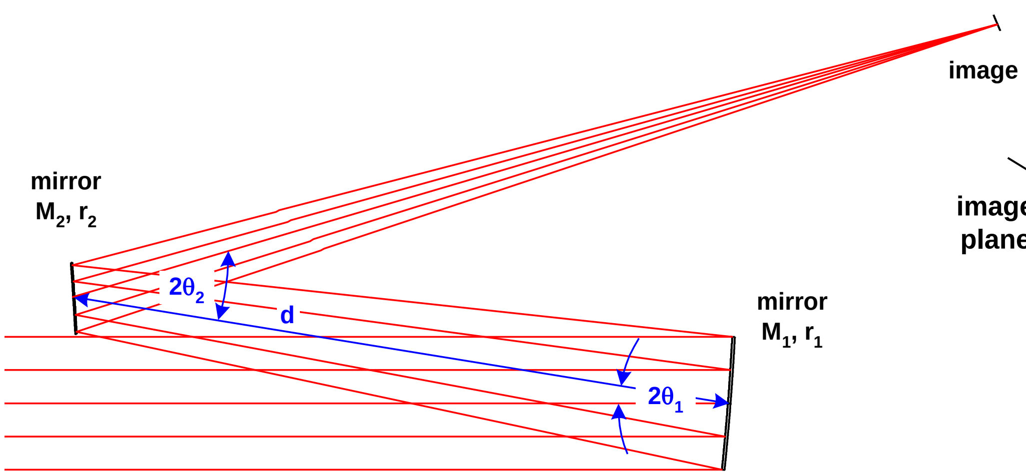


Schiefspiegler-Telescopes

- Telescopes with tilted elements
- Anastigmatic solution
  for two mirrors

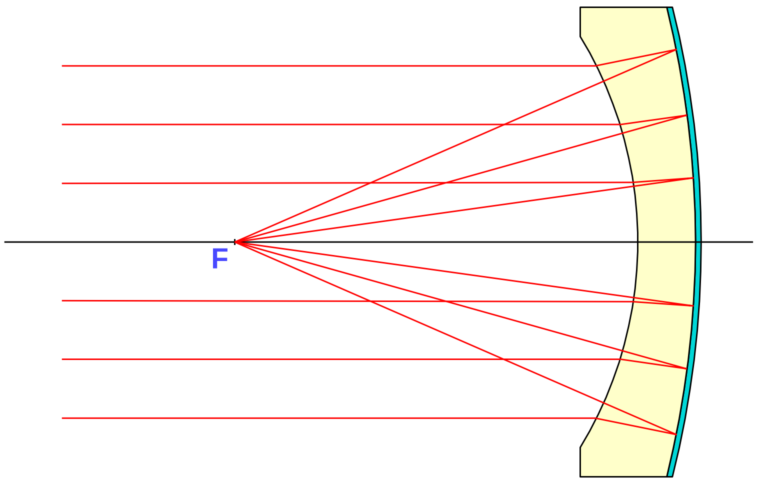
$$\frac{\theta_2}{\theta_2} = \frac{\sqrt{r_1 \cdot r_2}}{r_1 - 2d}$$

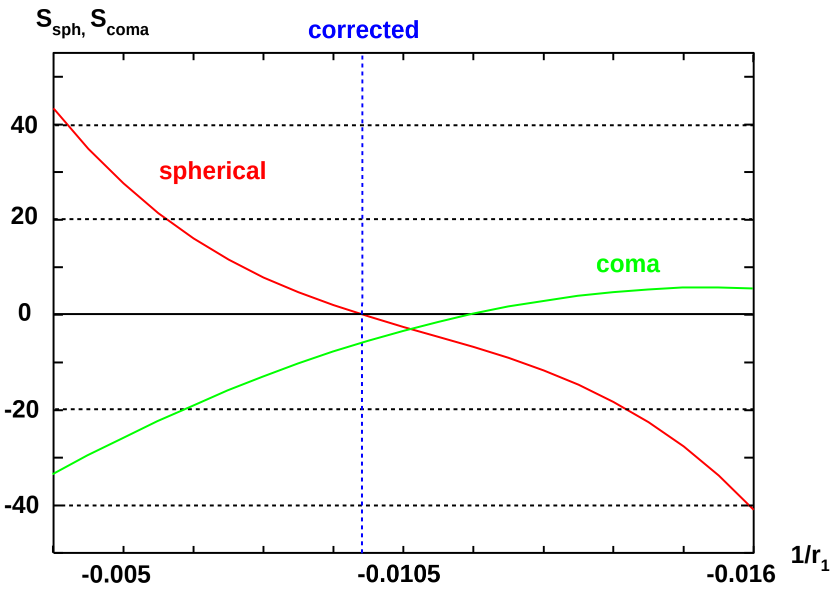




Mangin Mirror

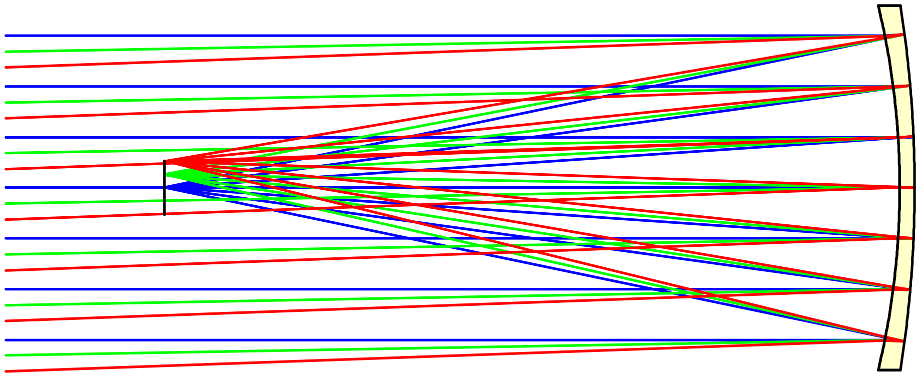
- Principle:
  Backside mirror, catadioptric lens
- Advantages:
  Mirror can be made spherical
  Refractive surface corrects spherical
  System can be made nearly aplanatic

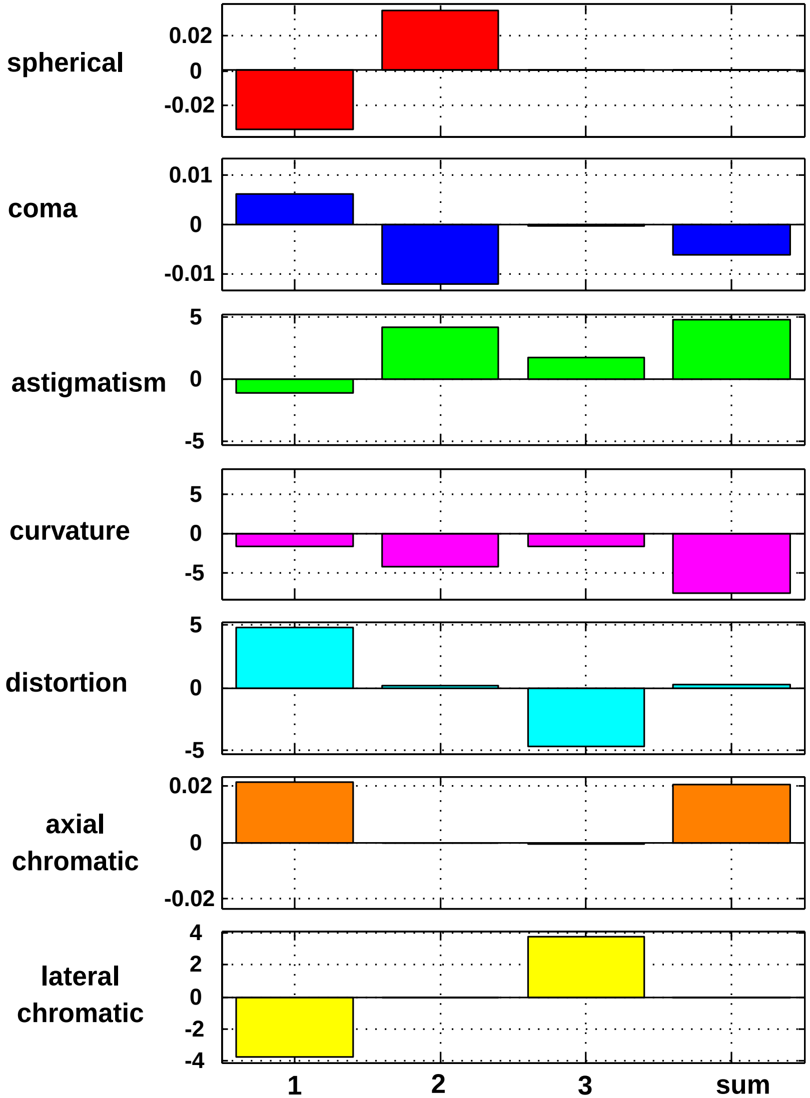




Mangin Mirror

- Seidel surface contributions of a real lens:
  Spherical correction perfect
  Residual axial chromatic unavoidable





Aberrations Limited by Vignetting

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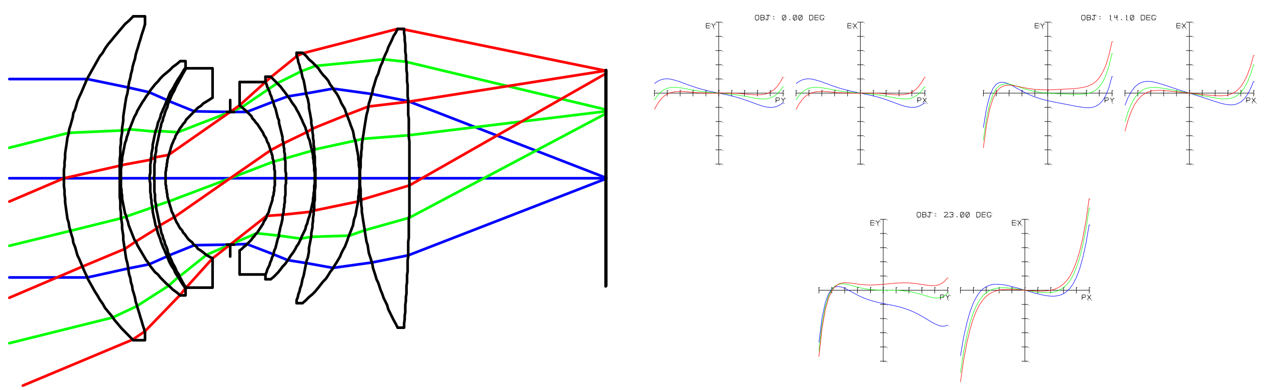
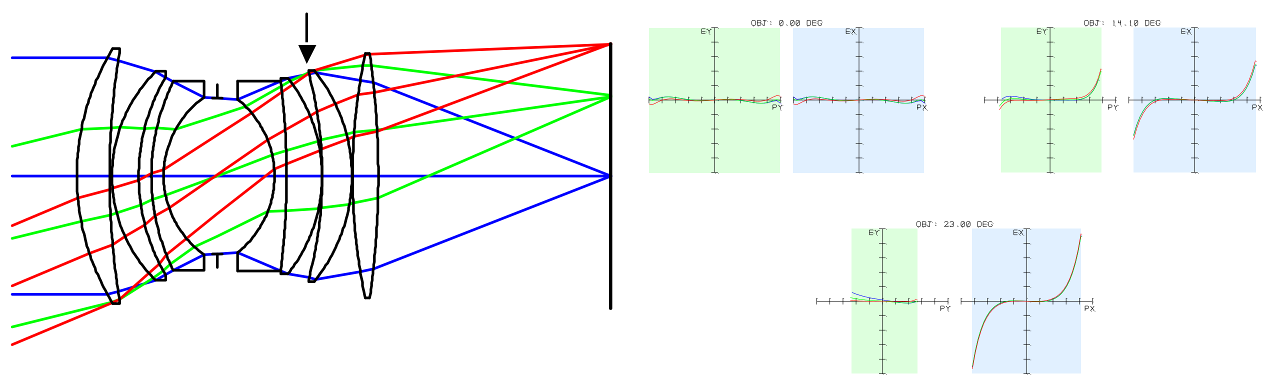
- Clipping of outer coma rays by vignetting
- Consequences:
  - reduced brightness
  - anisotropic resolution

without vignettierung



with vignettierung

tangential / sagittal



Ref: H.Zügge

Exercise: Telephoto Lens

A telephoto lens is a system with a focal length, that is considerably larger than the overall length of the system. The general approach is to combine a positive lens group with a negative group.

a) Establish a telephoto lens system with paraxial lenses for an incoming collimated ray bundle of diameter 10 mm. The numerical aperture after the first group should be NA = 0.1 and NA = 0.05 in the image space for λ = 587 nm. The total focal length should be 3 times larger than the free working distance. Determine the focal length of the system and of both lens groups.

b) Look for achromates for both groups, rescale the negative achromate, if the desired focal length is not available. Re-adjust the distances of the system by requiring the image sided numerical aperture. Is the system diffraction limited in performance ? Explain the result.

c) Now the wavelength is changed to dFC and a field points of 10° and 7° are introduced. The stop is located at the first surface. The focal length and the free working distance are kept constant. Now optimize the second lens group and allow also for larger diameter. Is the performance diffraction limited ? Finally optimize also the radii of the first lens group. What is the obtained performance ? What happens, if the second group is now reverted back ? What is the remaining dominant aberration type ?

d) Calculate the polychromatic modulation transfer function of the system on axis. What is the contrast at the spatial frequency 20 LP/mm ? Calculate the MTF behavior versus defocussing for this frequency at the central wavelength 587 nm. Determine the maximum defocussing values, that delivers a contrast not smaller than 50%.

Time is Over