



**Institute of
Applied Physics**

Friedrich-Schiller-Universität Jena

Imaging and Aberration Theory

Lecture 5: Aberrations representations

2018-11-16

Herbert Gross



Schedule - Imaging and aberration theory 2018

1	19.10.	Paraxial imaging	paraxial optics, fundamental laws of geometrical imaging, compound systems
2	26.10.	Pupils, Fourier optics, Hamiltonian coordinates	pupil definition, basic Fourier relationship, phase space, analogy optics and mechanics, Hamiltonian coordinates
3	02.11.	Eikonal	Fermat principle, stationary phase, Eikonals, relation rays-waves, geometrical approximation, inhomogeneous media
4	09.11.	Aberration expansions	single surface, general Taylor expansion, representations, various orders, stop shift formulas
5	16.11.	Representation of aberrations	different types of representations, fields of application, limitations and pitfalls, measurement of aberrations
6	23.11.	Spherical aberration	phenomenology, sph-free surfaces, skew spherical, correction of sph, aspherical surfaces, higher orders
7	30.11.	Distortion and coma	phenomenology, relation to sine condition, aplanatic systems, effect of stop position, various topics, correction options
8	07.12.	Astigmatism and curvature	phenomenology, Coddington equations, Petzval law, correction options
9	14.12.	Chromatical aberrations	Dispersion, axial chromatical aberration, transverse chromatical aberration, spherochromatism, secondary spectrum
10	21.12.	Sine condition, aplanatism and isoplanatism	Sine condition, isoplanatism, relation to coma and shift invariance, pupil aberrations, Herschel condition, relation to Fourier optics
11	11.01.	Wave aberrations	definition, various expansion forms, propagation of wave aberrations
12	18.01.	Zernike polynomials	special expansion for circular symmetry, problems, calculation, optimal balancing, influence of normalization, measurement
13	25.01.	Point spread function	ideal psf, psf with aberrations, Strehl ratio
14	01.02.	Transfer function	transfer function, resolution and contrast
15	08.02.	Additional topics	Vectorial aberrations, generalized surface contributions, Aldis theorem, intrinsic and induced aberrations, revertability

1. Stop shift formulas
2. Lens aberration contributions
3. Pupil aberrations
4. Representation of geometrical aberrations
5. Representation of wave aberrations
6. Miscellaneous
7. Aberration measurements



Refracting Surface VII: Eikonal

▪ Eikonal of 4th order

$$L_A^{(4)} = K \cdot \frac{(s-p)^4}{8p^4} (x^2 + y^2)^2 + S \cdot \frac{s^4}{8p^4} (x_p^2 + y_p^2)^2 + A \cdot \frac{s^2 \cdot (s-p)^2}{2p^4} (xx_p + yy_p)^2 \\ + P \cdot \frac{s^2 \cdot (s-p)^2}{4p^4} (x^2 + y^2)(xx_p + yy_p) - D \cdot \frac{s \cdot (s-p)^3}{2p^4} (x^2 + y^2)(xx_p + yy_p) - C \cdot \frac{s^3 \cdot (s-p)}{2p^4} (x^2 + y^2)(xx_p + yy_p)$$

▪ Coefficients

1. Spherical aberration

$$K = -\frac{(n'-n)b}{R^3} - ns \cdot \left(\frac{1}{Rs} - \frac{1}{s_p^2} \right)^2 + n's' \cdot \left(\frac{1}{Rs'} - \frac{1}{s_p'^2} \right)^2$$

2. Astigmatism

$$S = -\frac{(n'-n)b}{R^3} - Q^2 \cdot \left(\frac{1}{ns} - \frac{1}{n's'} \right)$$

3. Field curvature

$$A = -\frac{(n'-n)b}{R^3} - Q_p^2 \cdot \left(\frac{1}{ns} - \frac{1}{n's'} \right)$$

4. Distortion

$$P = -\frac{(n'-n)b}{R^3} - QQ_p \cdot \left(\frac{1}{ns} - \frac{1}{n's'} \right) + Q(Q - Q_p) \cdot \left(\frac{1}{ns_p} - \frac{1}{n's_p'} \right)$$

5. Coma

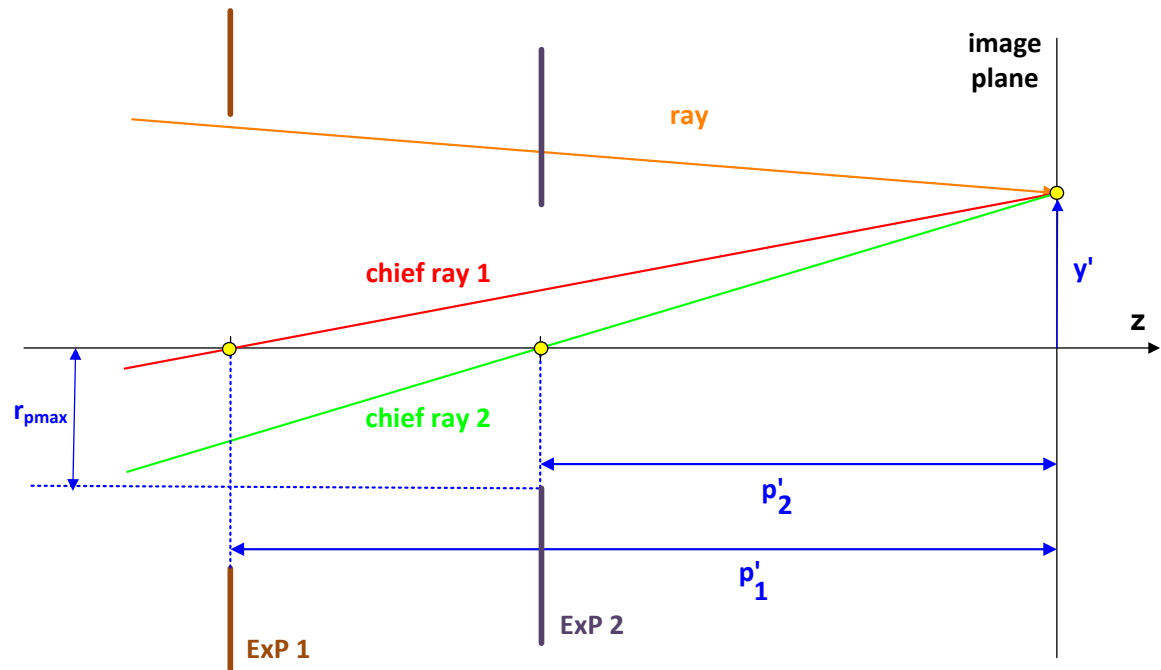
$$D = -\frac{(n'-n)b}{R^3} - Q_p^2 \cdot \left(\frac{1}{ns} - \frac{1}{n's'} \right) + Q_p(Q - Q_p) \cdot \left(\frac{1}{ns_p} - \frac{1}{n's_p'} \right)$$

$$C = -\frac{(n'-n)b}{R^3} - QQ_p \cdot \left(\frac{1}{ns} - \frac{1}{n's'} \right)$$



Stop Shift Formulas

- If the stop is moved, the chief ray takes a modified way through the system
- Approach: expansion of the surface coefficient formulas for small changes in the pupil position p , p'
- The stop shift formulas shows the change of the Seidel coefficients due to this effect
- Also possible:
set of formulas for object or image shift
applicable for curved objects



Stop Shift Formulas

- Stop shift formulas explicit with the help of the moving parameter

$$\delta E = \frac{\bar{h}_{new} - \bar{h}_{old}}{h}$$

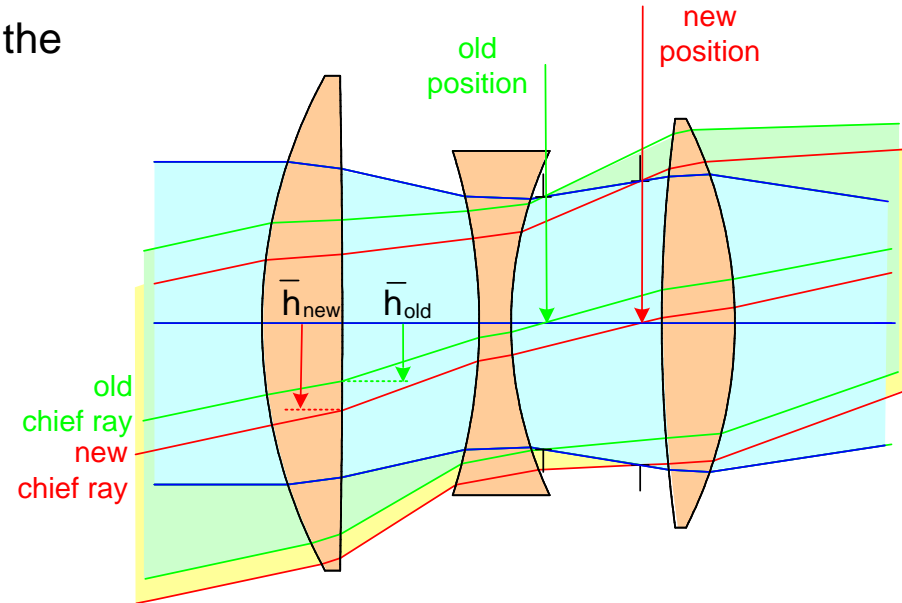
sph $S_I^* = S_I$

coma $S_{II}^* = S_{II} + \delta E \cdot S_I$

ast $S_{III}^* = S_{III} + \delta E \cdot S_{II} + \delta E^2 \cdot S_I$

curv $S_{IV}^* = S_{IV}$

dist $S_V^* = S_V + \delta E \cdot (3S_{III} + S_{IV}) + 3\delta E^2 \cdot S_{II} + \delta E^3 \cdot S_I$



- Mix of aberration types due to stop shift: induced aberrations

Examples:

- spherical aberration induces coma
- coma induces astigmatism



Lens Contributions of Seidel

- In 3rd order (Seidel) :

Additive contributions of thin lenses (equal ω) to the total aberration value
(stop at lens position)

- Spherical aberration

X: lens bending

M: position parameter

$$S_{lens} = \frac{1}{32n(n-1)f^3} \left[\frac{n^3}{n-1} + \frac{n+2}{n-1} \cdot \left(X - \frac{2(n^2-1)}{n+2} \cdot M \right)^2 - \frac{n^2(n-1)}{n+2} \cdot M^2 \right]$$

- Coma

$$C_{lens} = \frac{1}{4ns'f^2} \cdot \left[\frac{n+1}{n-1} X - (2n+1)M \right]$$

- Astigmatism

$$A_{lens} = -\frac{1}{2f \cdot s'^2}$$

- Field curvature

$$P_{lens} = -\frac{n+1}{4nf \cdot s'^2}$$

- Distortion

$$D_{lens} = 0$$

- Spherical aberration

$$S_{lens} = \frac{1}{32n(n-1)f^3} \left[\frac{n^3}{n-1} + \frac{n+2}{n-1} \cdot \left(X - \frac{2(n^2-1)}{n+2} \cdot M \right)^2 - \frac{n^2(n-1)}{n+2} \cdot M^2 \right]$$

- Special impact on correction:

1. Special quadratic dependence on bending X

Minimum at

$$X_{sph \min} = -\frac{2(n^2-1)}{n+2} M$$

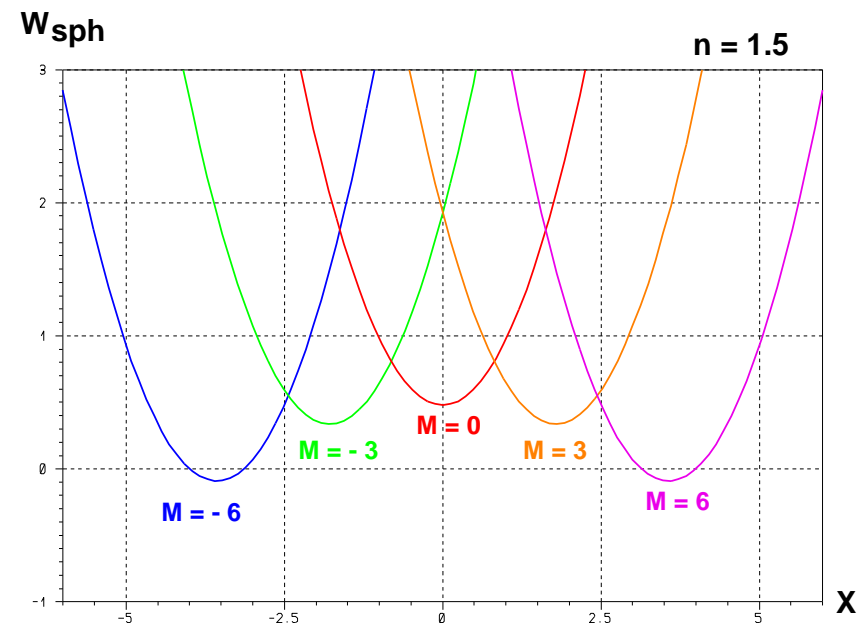
2. No correction for small n and M

3. Correction for large n: infrared materials

M: virtual imaging

Limiting value

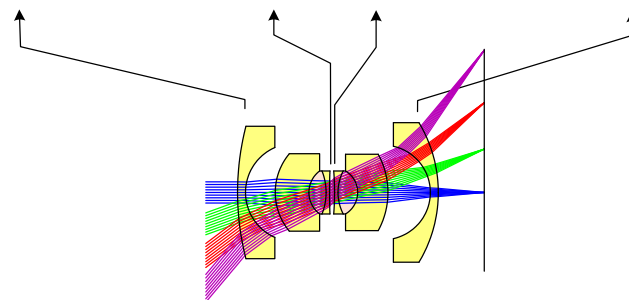
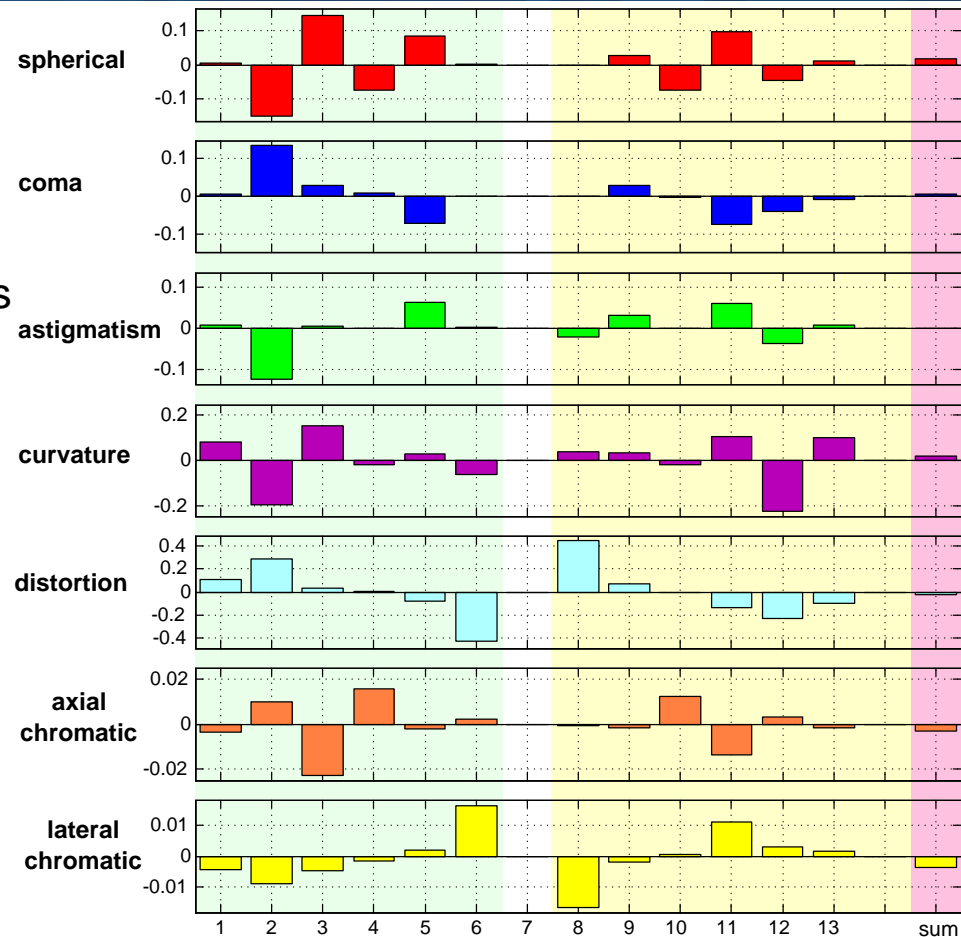
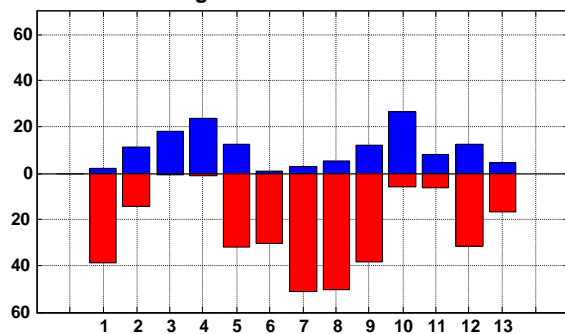
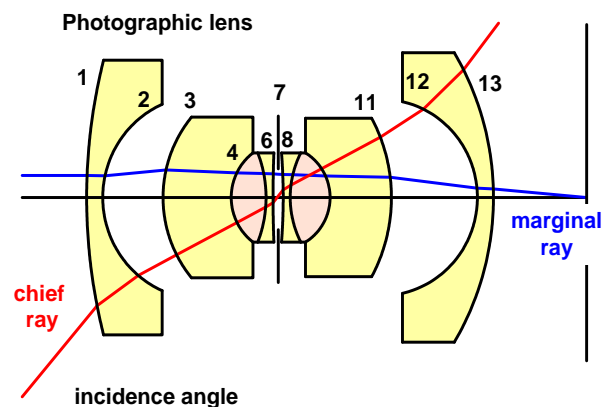
$$M_{s=0}^2 = \frac{n(n+2)}{(n-1)^2}$$



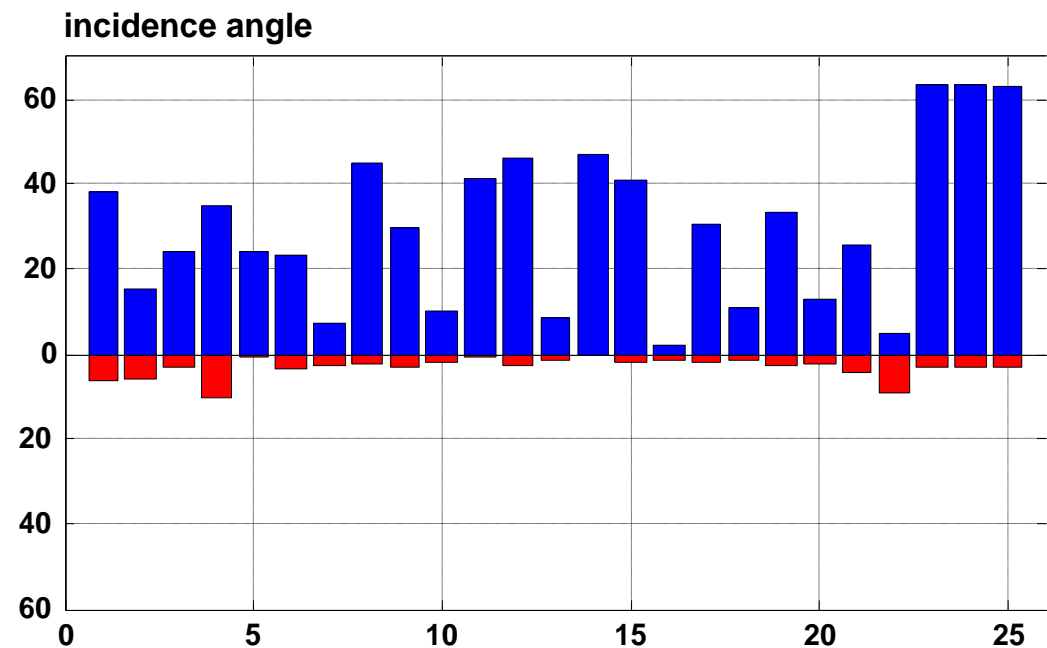
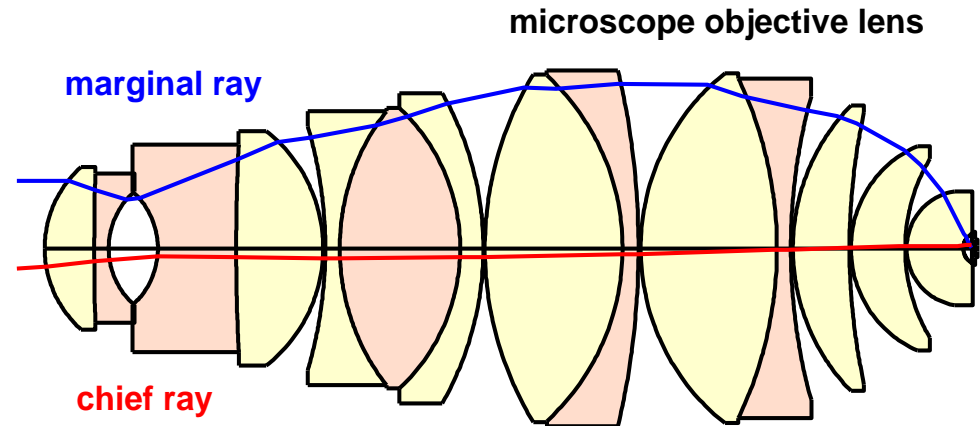


Photographic lens

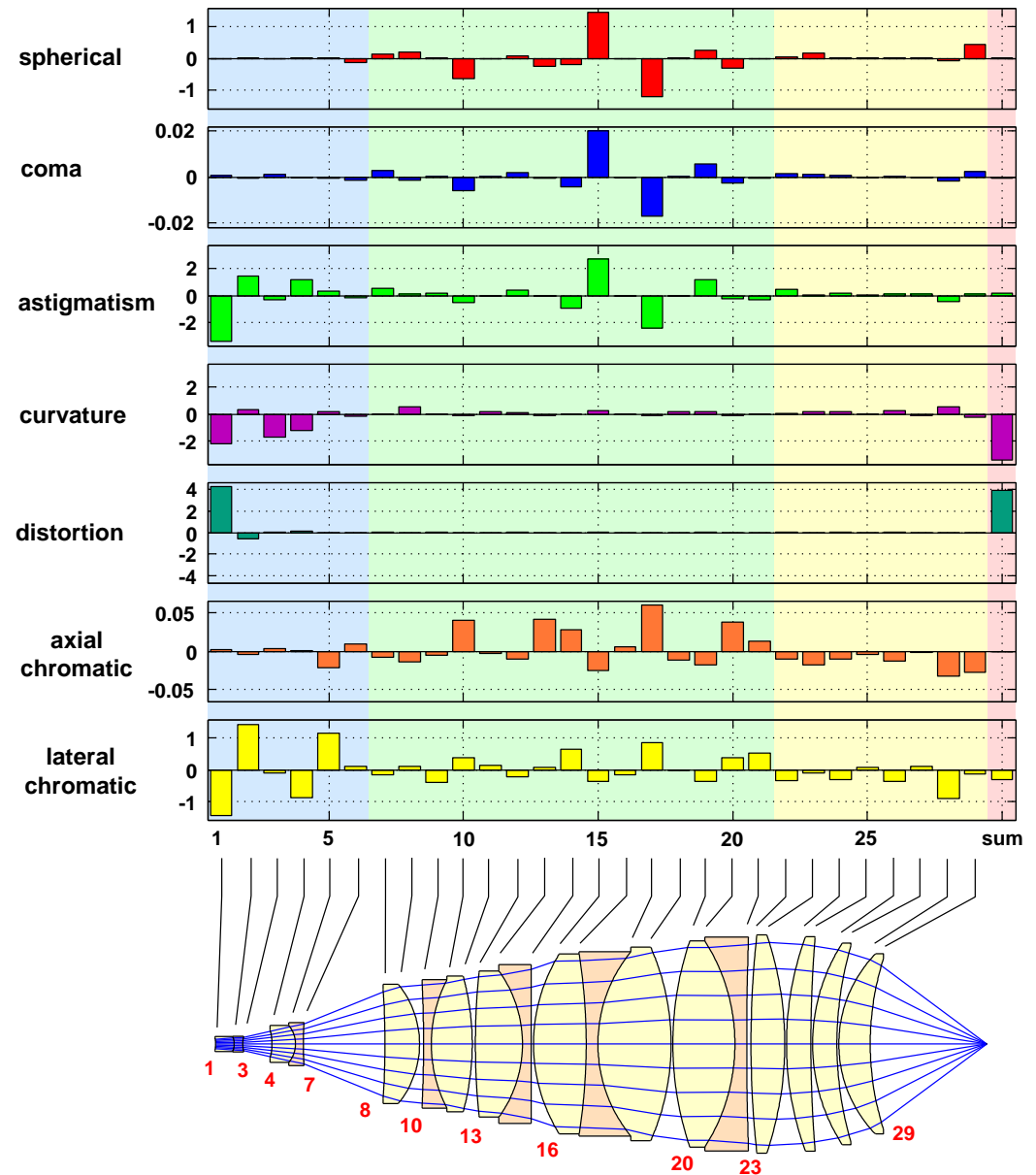
- Incidence angles for chief and marginal ray
- Field dominant system
- Quasi symmetry can be seen at the surface contributions of field aberrations
- Symmetry disturbed for spherical aberration



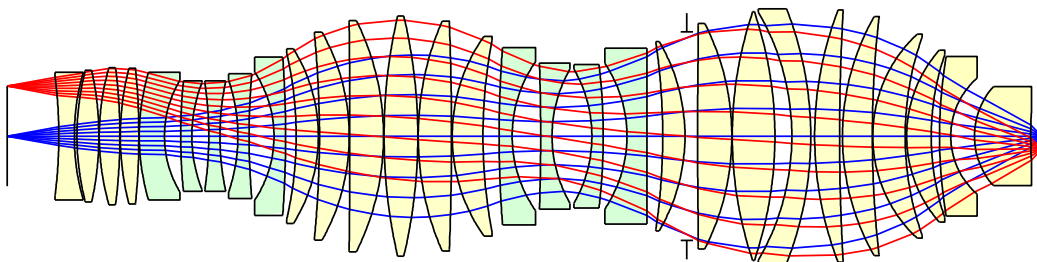
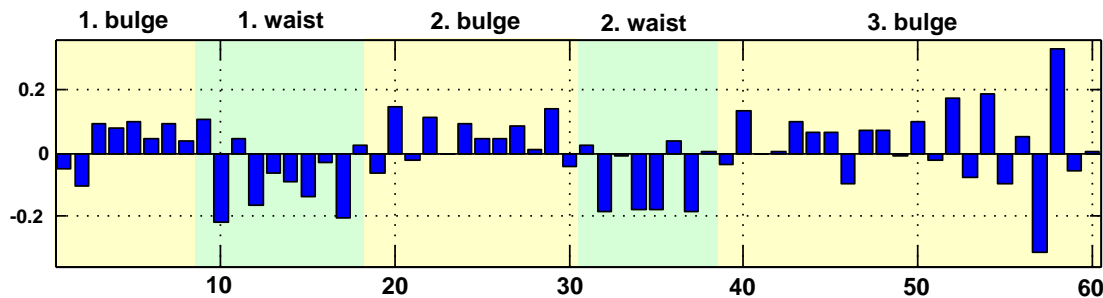
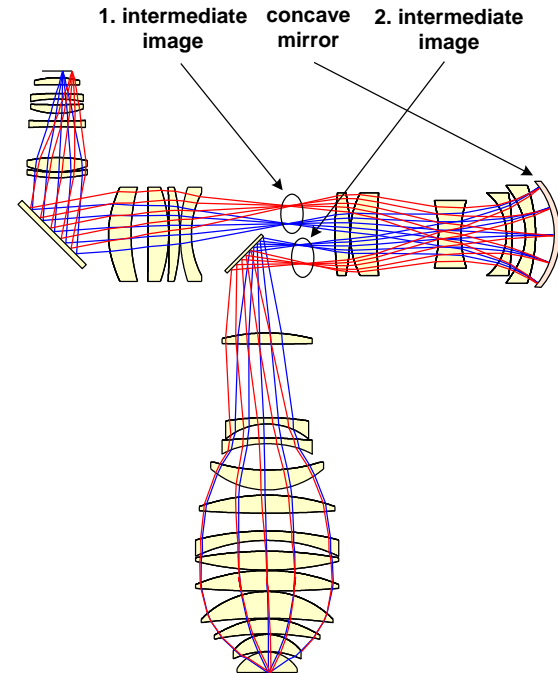
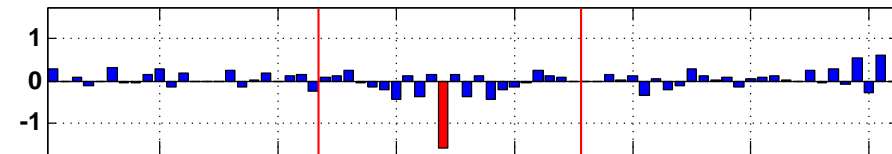
- Incidence angles for chief and marginal ray
- Aperture dominant system



- Large distance system
- Problems with large diameters
- Aplanatic front group
- Not corrected for curvature and distortion
- Astigmatic contributions of cemented surfaces corrected by rear group
- Sign of lateral chromatic aberration in front group



- Large effect of mirror on field curvature
- Typical bulge structure shows the correction of field curvature according to the Petzval theorem





Primary Aberration Spot Shapes

- Simplified set of Seidel formulas:
field point only in y' considered

$$\Delta y' = S' \cdot r_p'^3 \cos \varphi_p + C' \cdot y' \cdot r_p'^2 (2 + \cos 2\varphi_p) + (2A' + P') \cdot y'^2 \cdot r_p' \cos \varphi_p + D' \cdot y'^3$$

$$\Delta x' = S' \cdot r_p'^3 \sin \varphi_p + C' \cdot y' \cdot r_p'^2 \cdot \sin 2\varphi_p + P' \cdot y'^2 \cdot r_p' \sin \varphi_p$$

- Spherical aberration S:
circle

$$\Delta y' = S' \cdot r_p'^3 \cos \varphi_p, \quad \Delta x' = S' \cdot r_p'^3 \sin \varphi_p$$

$$\Delta x'^2 + \Delta y'^2 = S'^2 \cdot r_p'^6$$

- Coma:
shifted circle

$$\Delta y' = C' \cdot y' \cdot r_p'^2 \cdot (2 + \cos 2\varphi_p), \quad \Delta x' = C' \cdot y' \cdot r_p'^2 \cdot \sin 2\varphi_p$$

$$\Delta x'^2 + (\Delta y' - 2C' y' r_p'^2)^2 = C'^2 y'^2 r_p'^4$$

- Astigmatism:
focal line

$$\Delta y' = 2A' \cdot y'^2 \cdot r_p' \cos \varphi_p, \quad \Delta x' = 0$$

- Field curvature:
circle

$$\Delta y' = P' \cdot y'^2 \cdot r_p' \cos \varphi_p, \quad \Delta x' = P' \cdot y'^2 \cdot r_p' \sin \varphi_p$$

$$\Delta x'^2 + \Delta y'^2 = P'^2 y'^4 r_p'^2$$

- Distortion:
shifted point

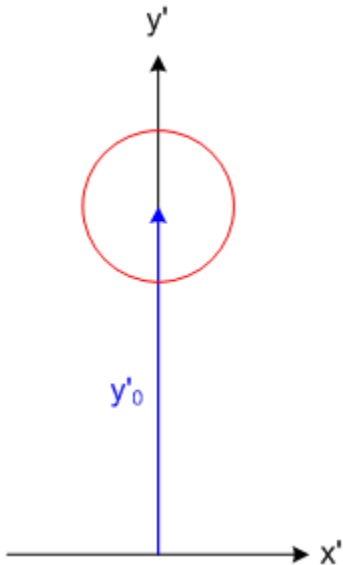
$$\Delta y' = D' \cdot y'^3, \quad \Delta x' = 0$$



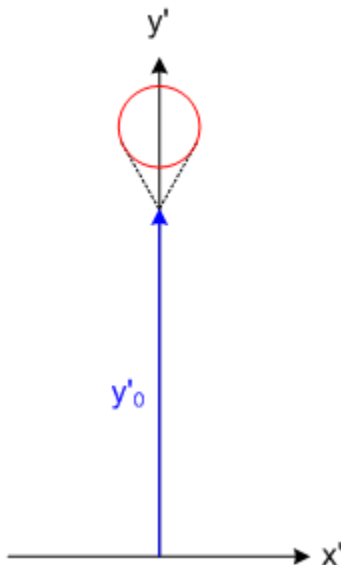
Primary Aberration Spot Shapes

▪ Schematically:

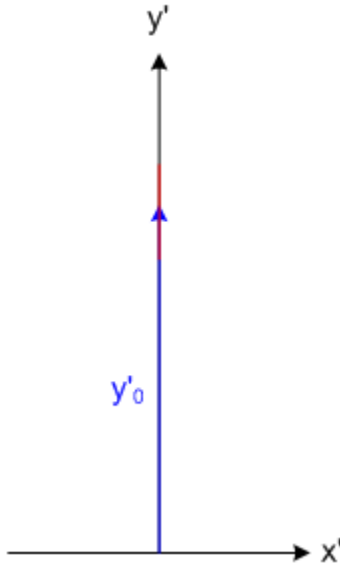
1) spherical aberration



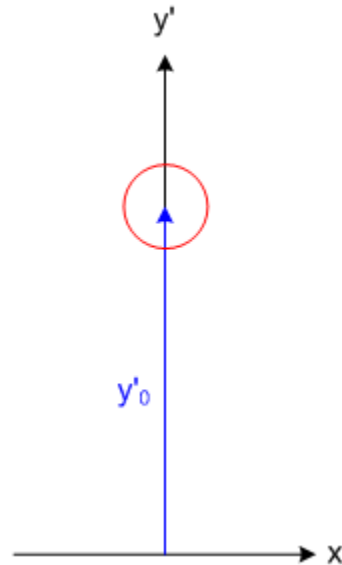
2) coma



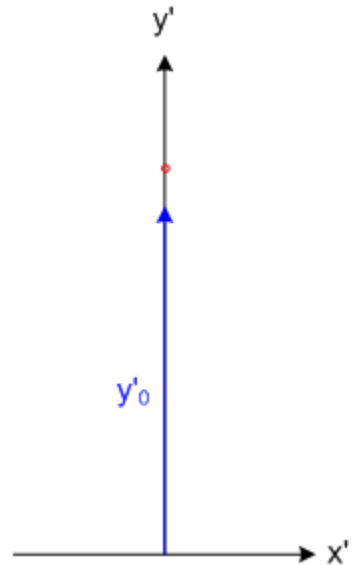
3) astigmatism



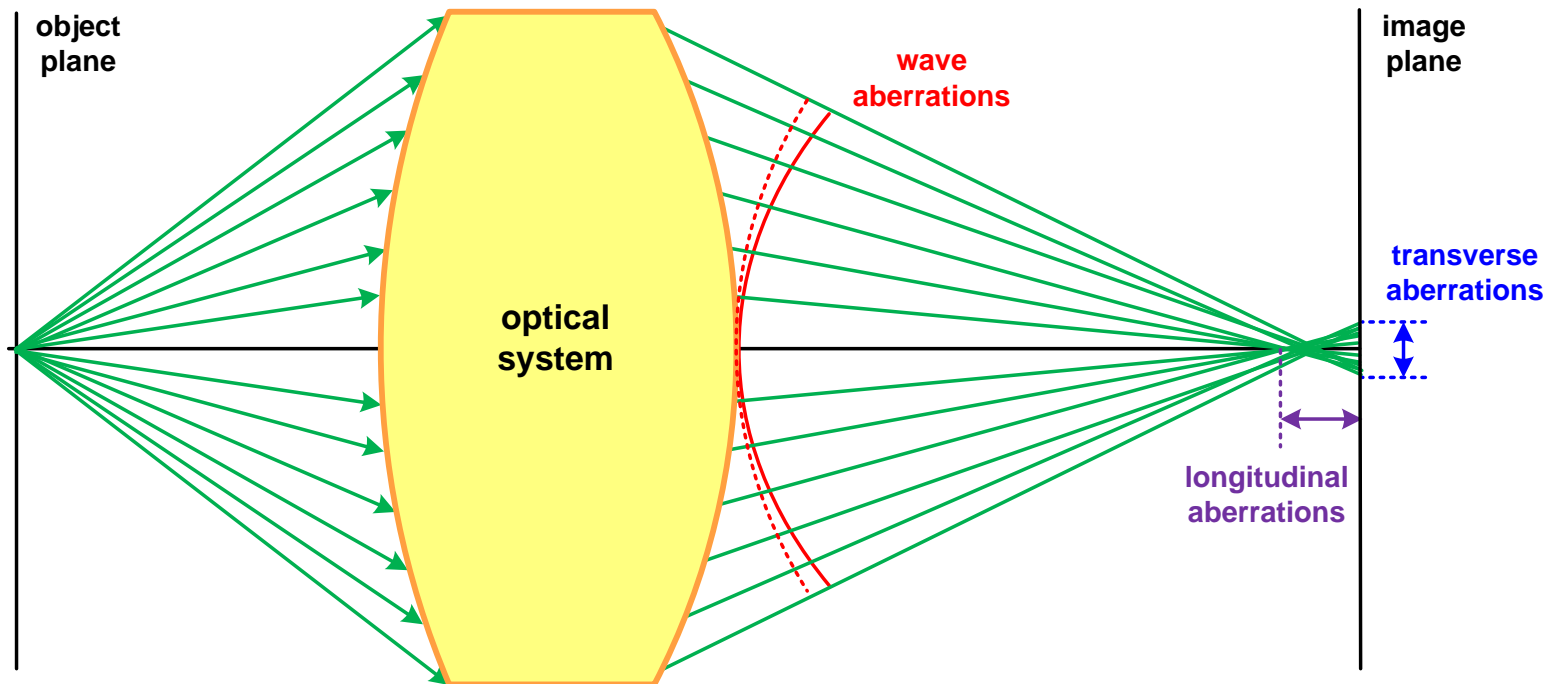
4) field curvature



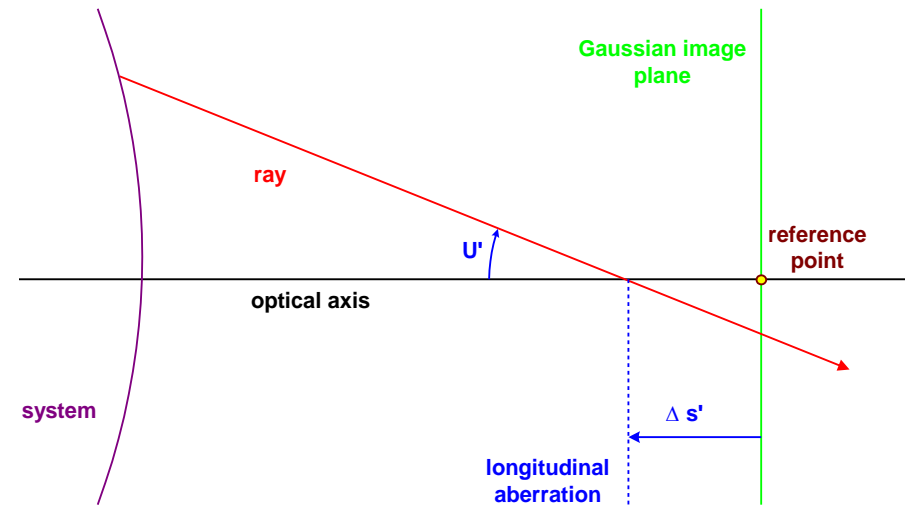
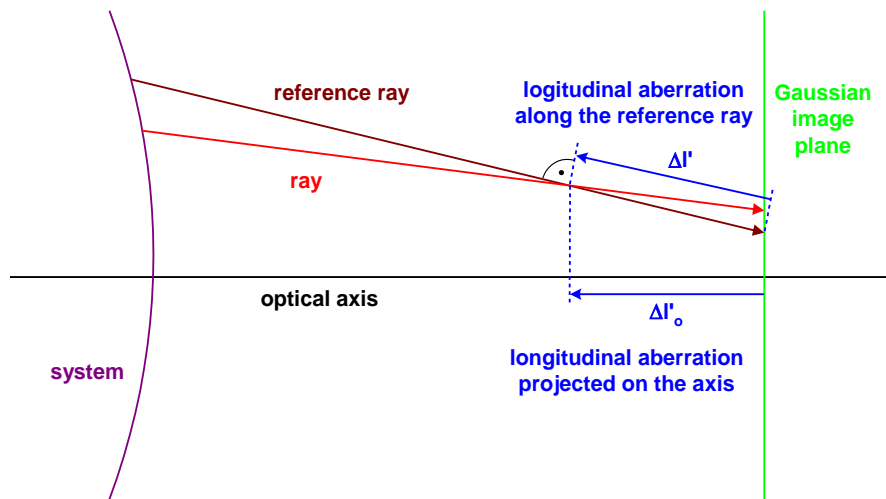
5) distortion



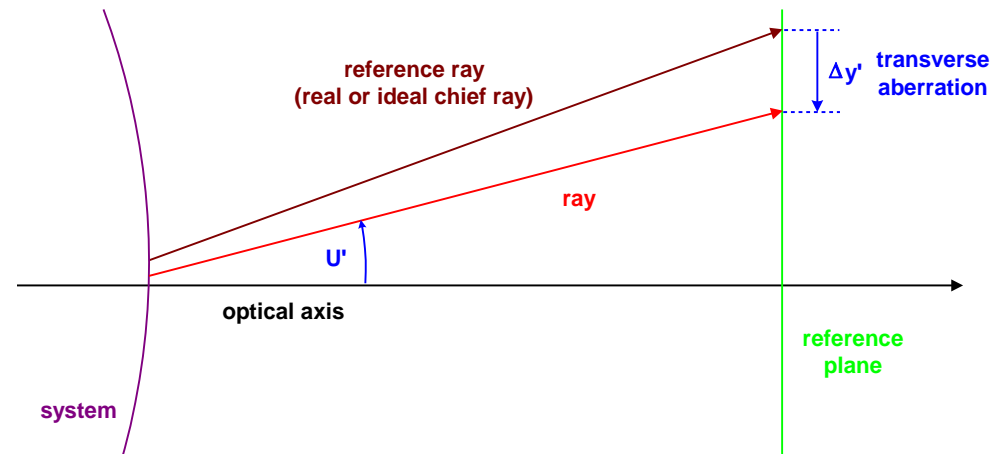
- Perfect optical image:
All rays coming from one object point intersect in one image point
- Real system with aberrations:
 1. transverse aberrations in the image plane
 2. longitudinal aberrations from the image plane
 3. wave aberrations in the exit pupil



- Longitudinal aberrations Δs



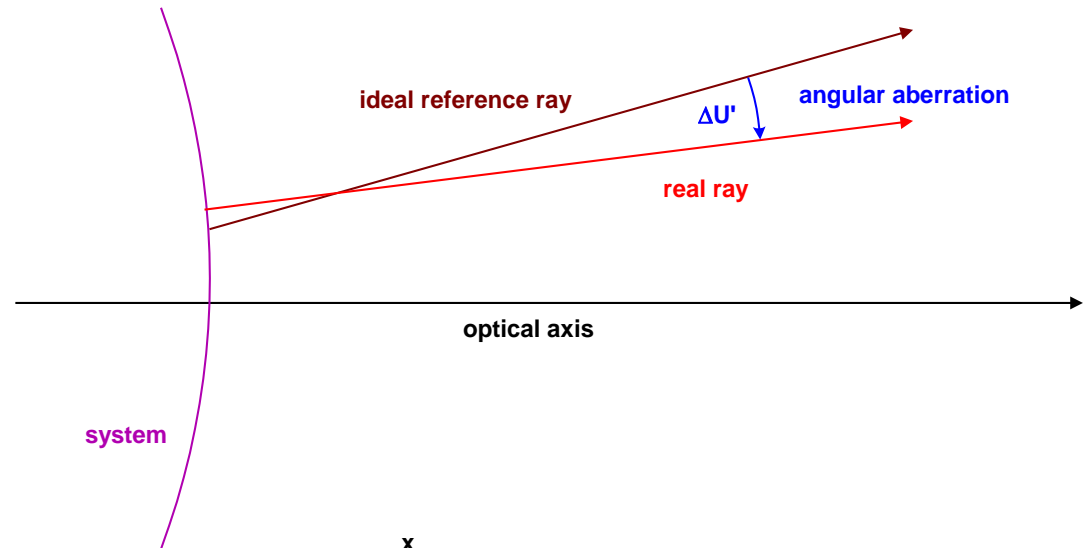
- Transverse aberrations Δy





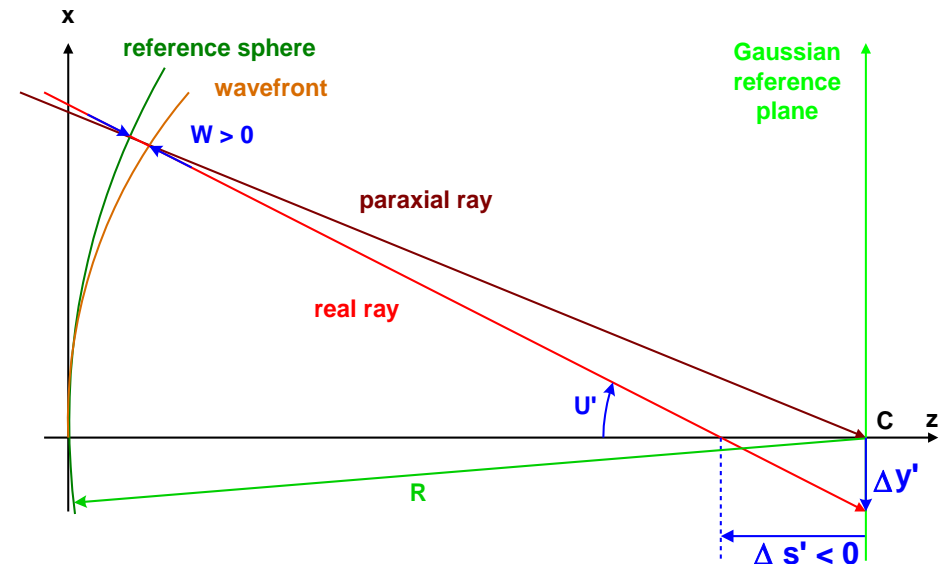
Representation of Geometrical Aberrations

- Angle aberrations Δu

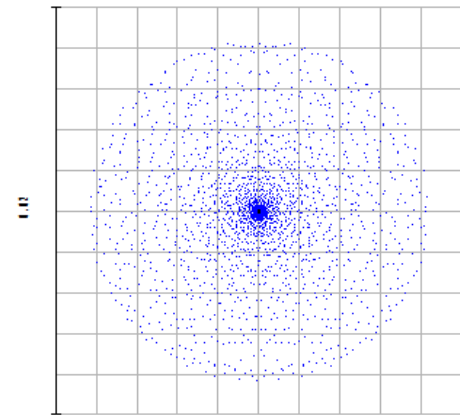
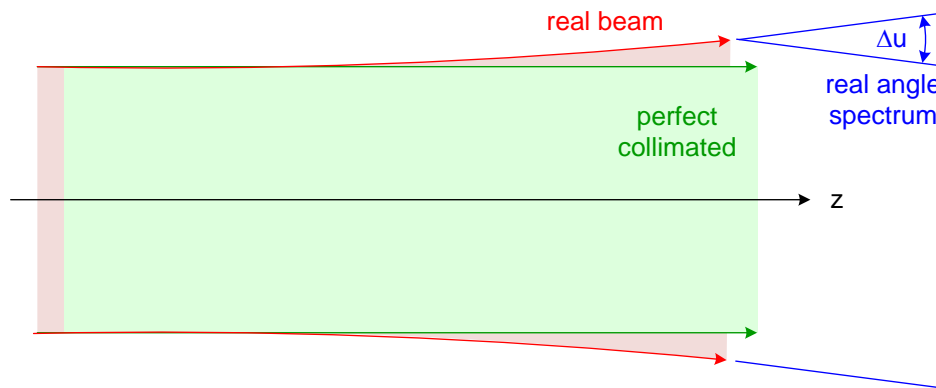


- Wave aberrations ΔW

$$\Delta s' = \frac{R}{y_p} \cdot \Delta y' = \frac{\Delta y'}{\sin u'} = -\frac{R^2}{y_p} \cdot \frac{\partial W(x_p, y_p)}{\partial y_p}$$



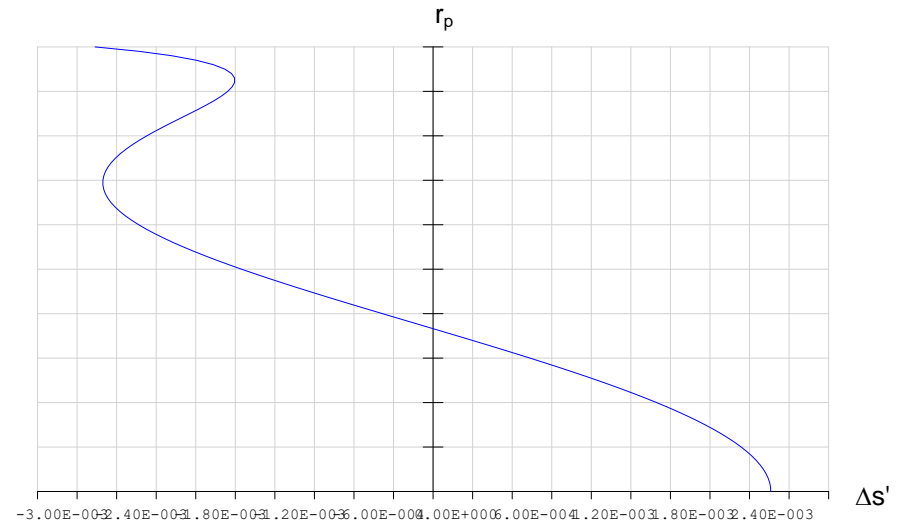
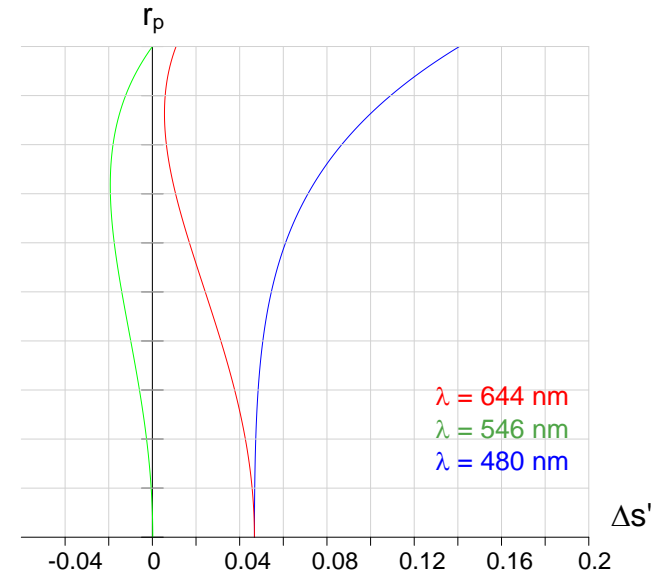
- Angle aberrations for a ray bundle:
deviation of every ray from common direction of the collimated ray bundle
- Representation as a conventional spot diagram
- Quantitative spreading of the collimated bundle in mrad / °

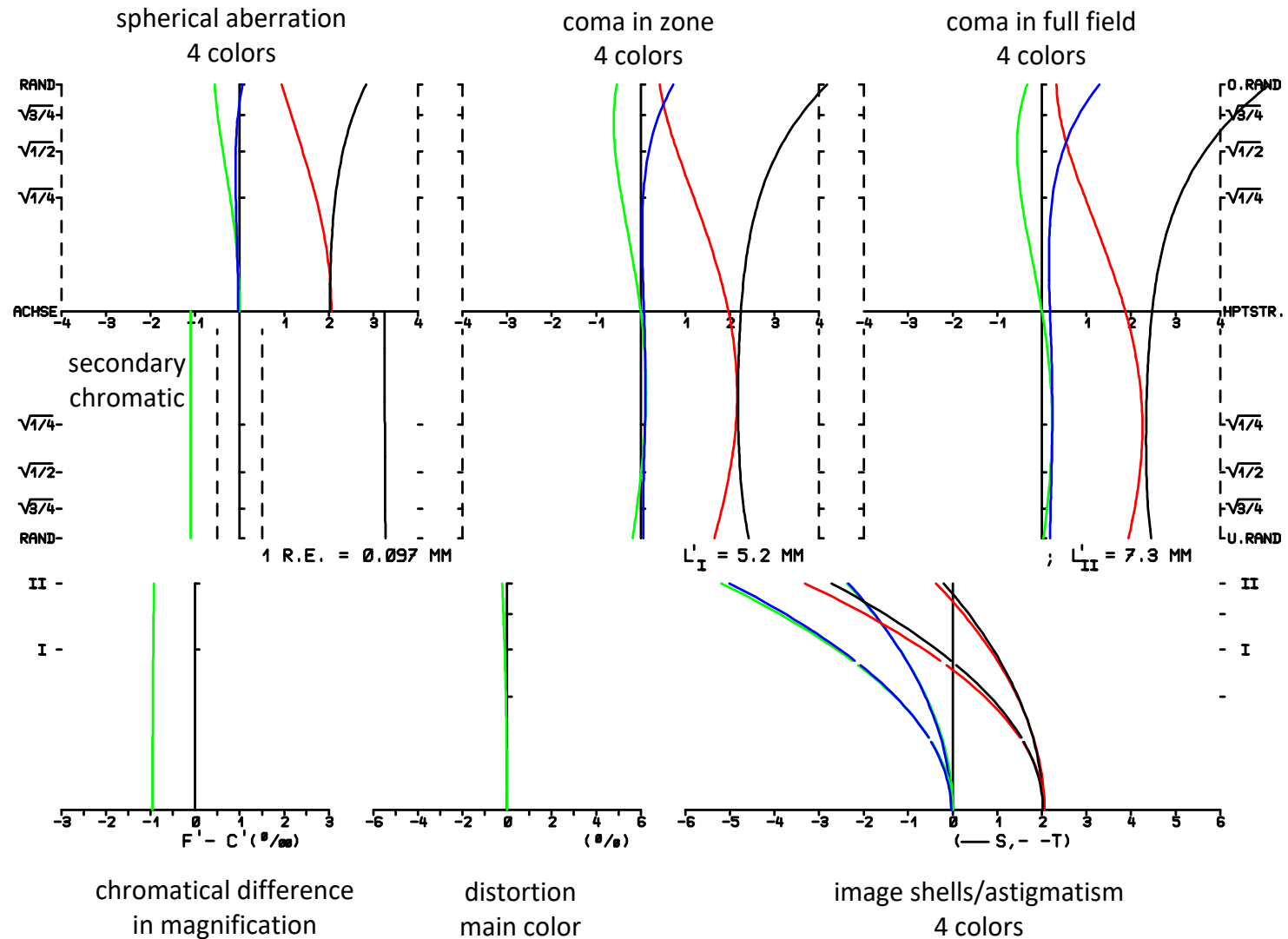




Aperture Dependence of Longitudinal Aberration

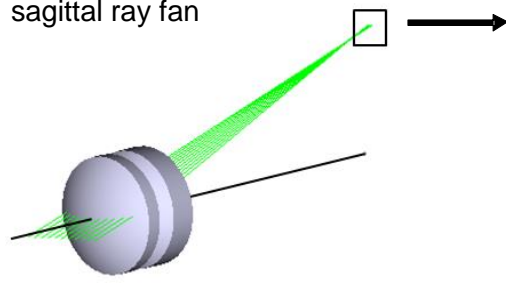
- Typical representation:
Longitudinal aberration as function of aperture
(pupil coordinate)
- If correction at the edge: maximum residuum
at the zone $1/\sqrt{2}$
- Typical: largest gradients at the edge
- Correcting aspheres or high NA of
higher order:
oscillatory behavior



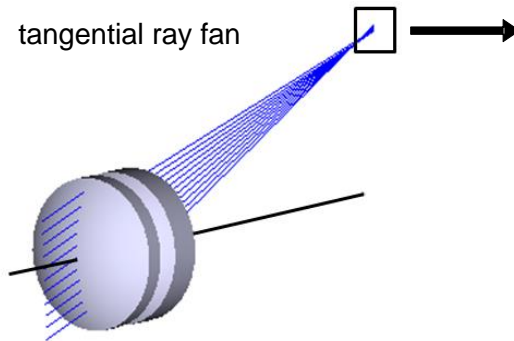


- Ray plots
- Spot diagrams

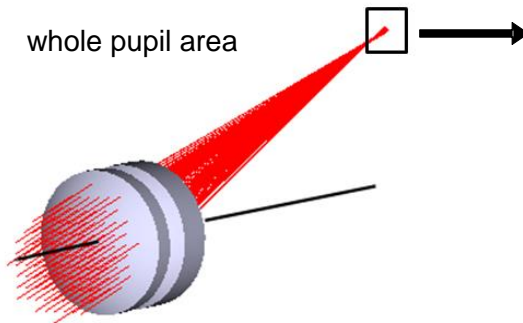
sagittal ray fan



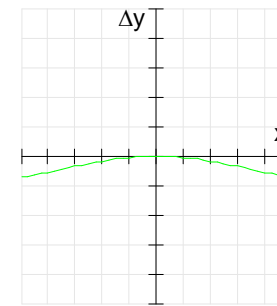
tangential ray fan



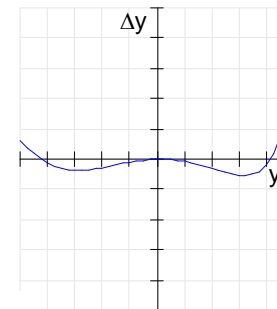
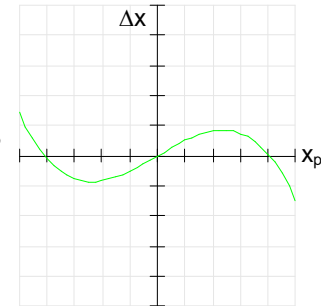
whole pupil area



tangential aberration



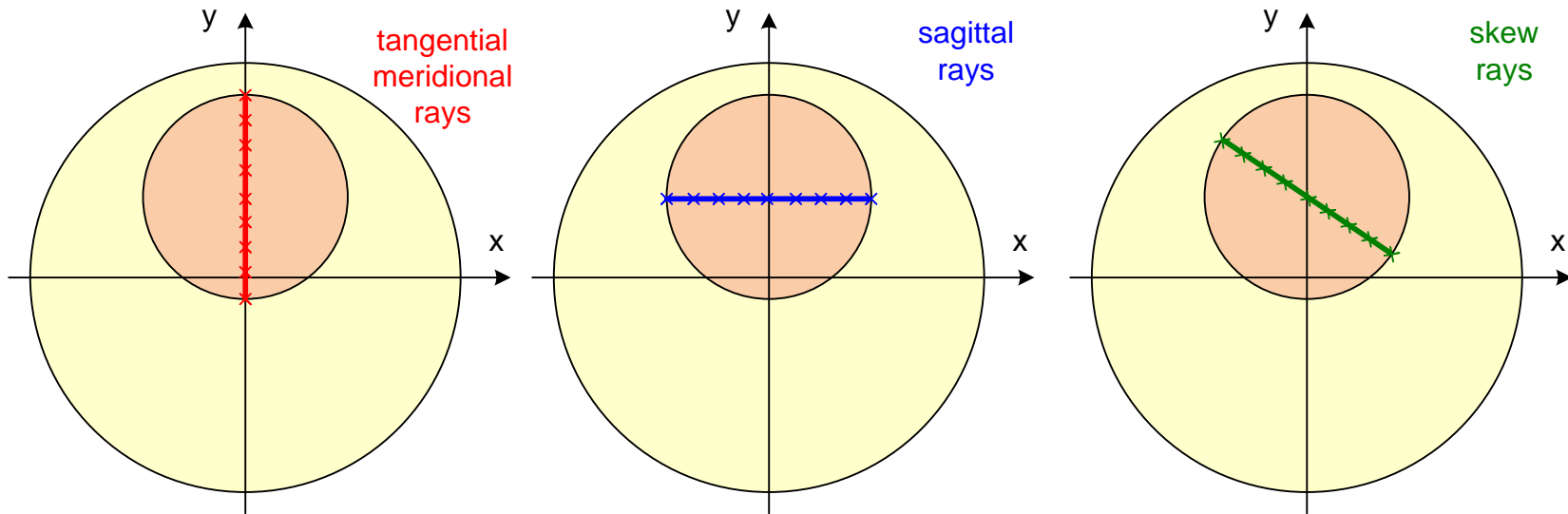
sagittal aberration





Ray Selection Planes

- Tangential / sagittal / skew rays
- View along optical axis





Transverse Aberrations

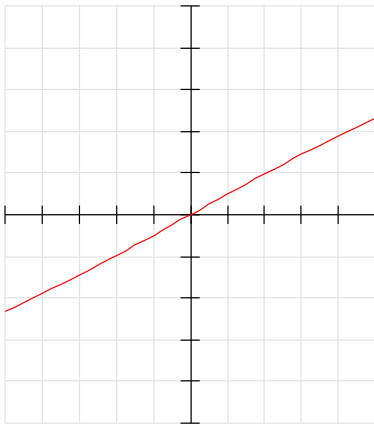
- Typical low order polynomial contributions for:
defocus, coma, spherical aberration, lateral color
- This allows a quick classification of real curves

$$\Delta y' = K' \cdot r_p' \cos \varphi_p$$

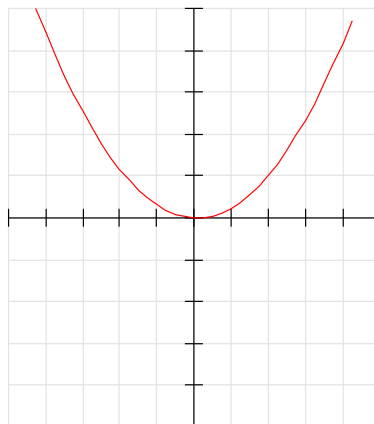
$$\Delta y' = S' \cdot r_p'^3 \cos \varphi_p$$

$$\Delta y' = C' \cdot y' \cdot r_p'^2 \cdot (2 + \cos 2\varphi_p)$$

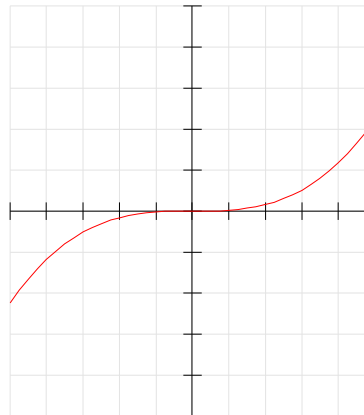
**linear:
defocus**



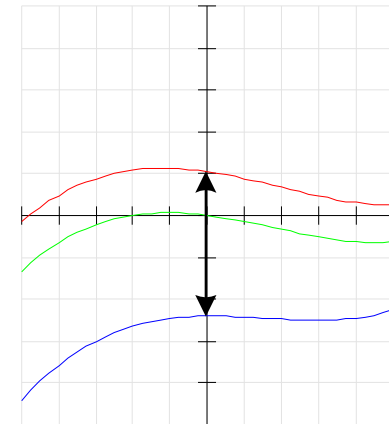
**quadratic:
coma**



**cubic:
spherical**



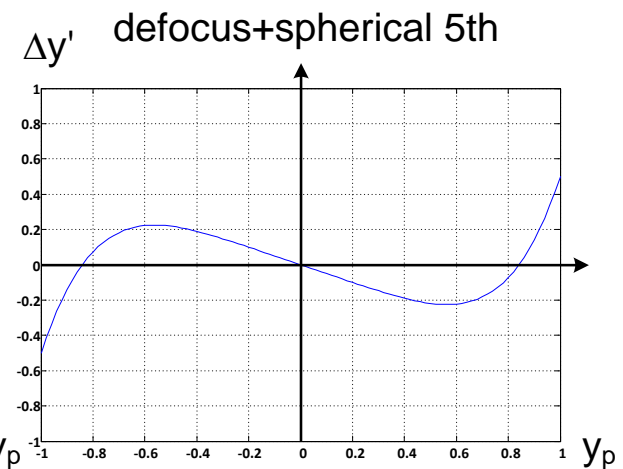
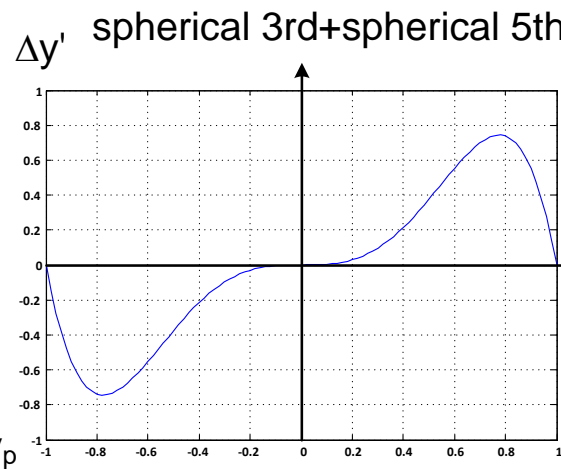
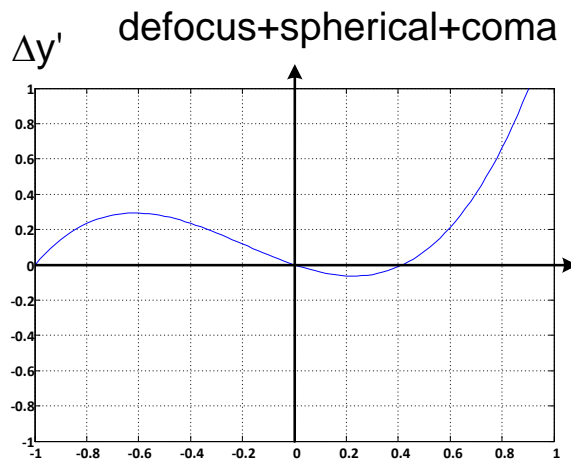
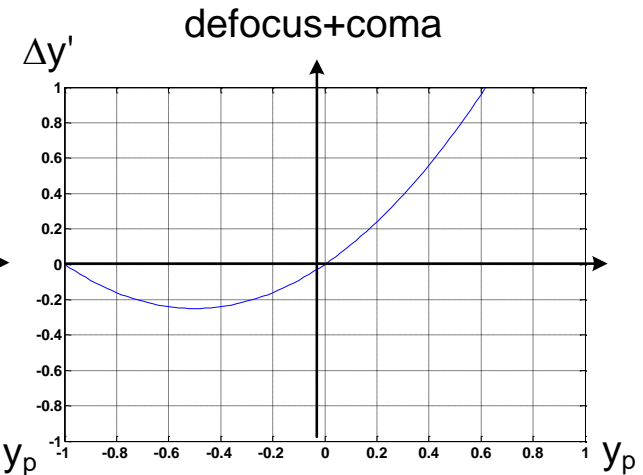
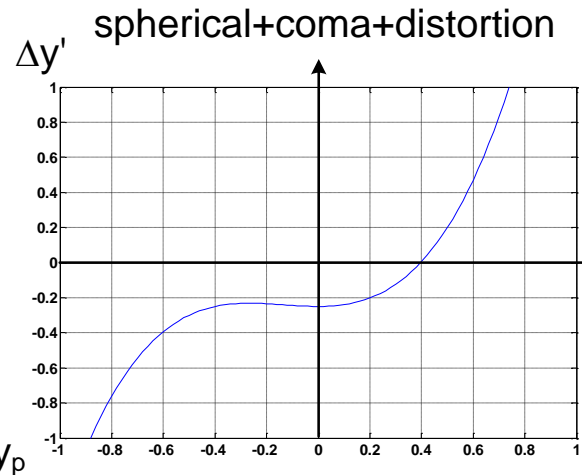
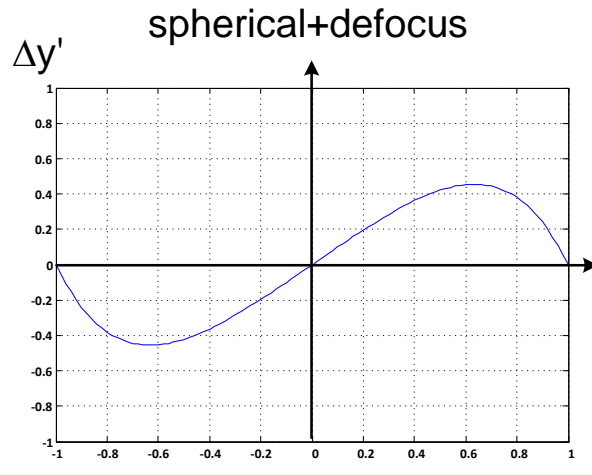
**offset:
lateral color**





Interpretation of Transverse Aberrations

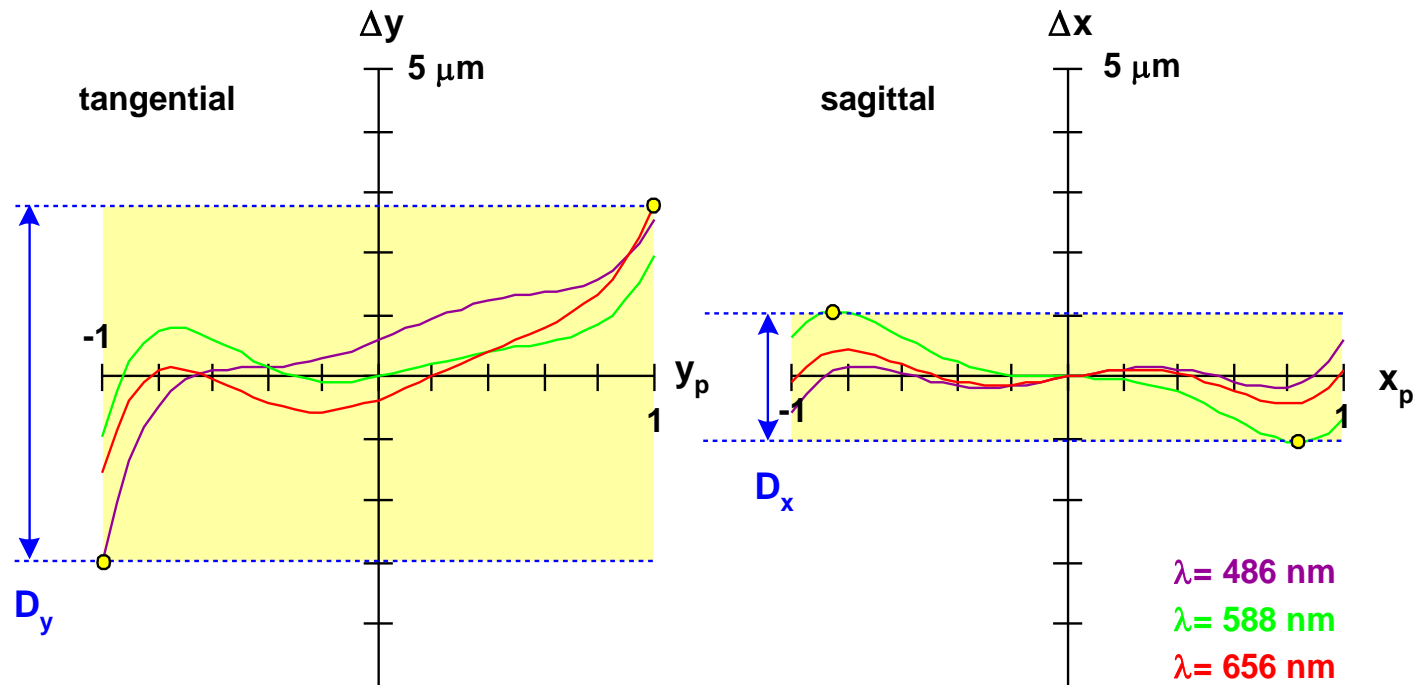
Combinations of basic shapes





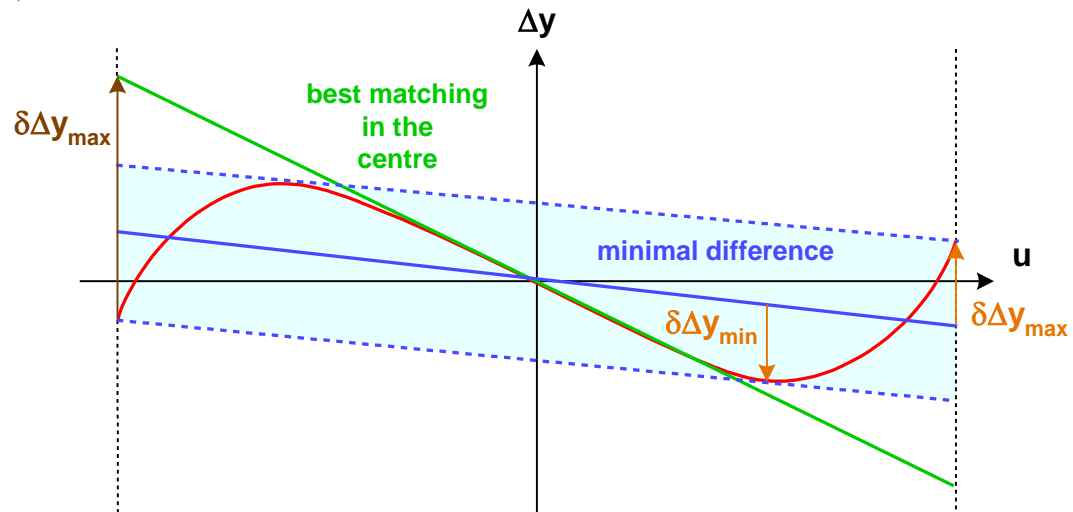
Transverse Aberrations

- Classical aberration curves
- Strong relation to spot diagram
- Usually only linear sampling along the x-, y-axis
no information in the quadrant of the aperture



Best Image plane

- Best resolution:
 - bright central peak in spot
 - tangent at transverse aberration curve
- Best contrast:
 - mean straight line over complete pupil of transverse aberration curve
 - smallest maximal deviation
- Different criteria give slightly different best image planes

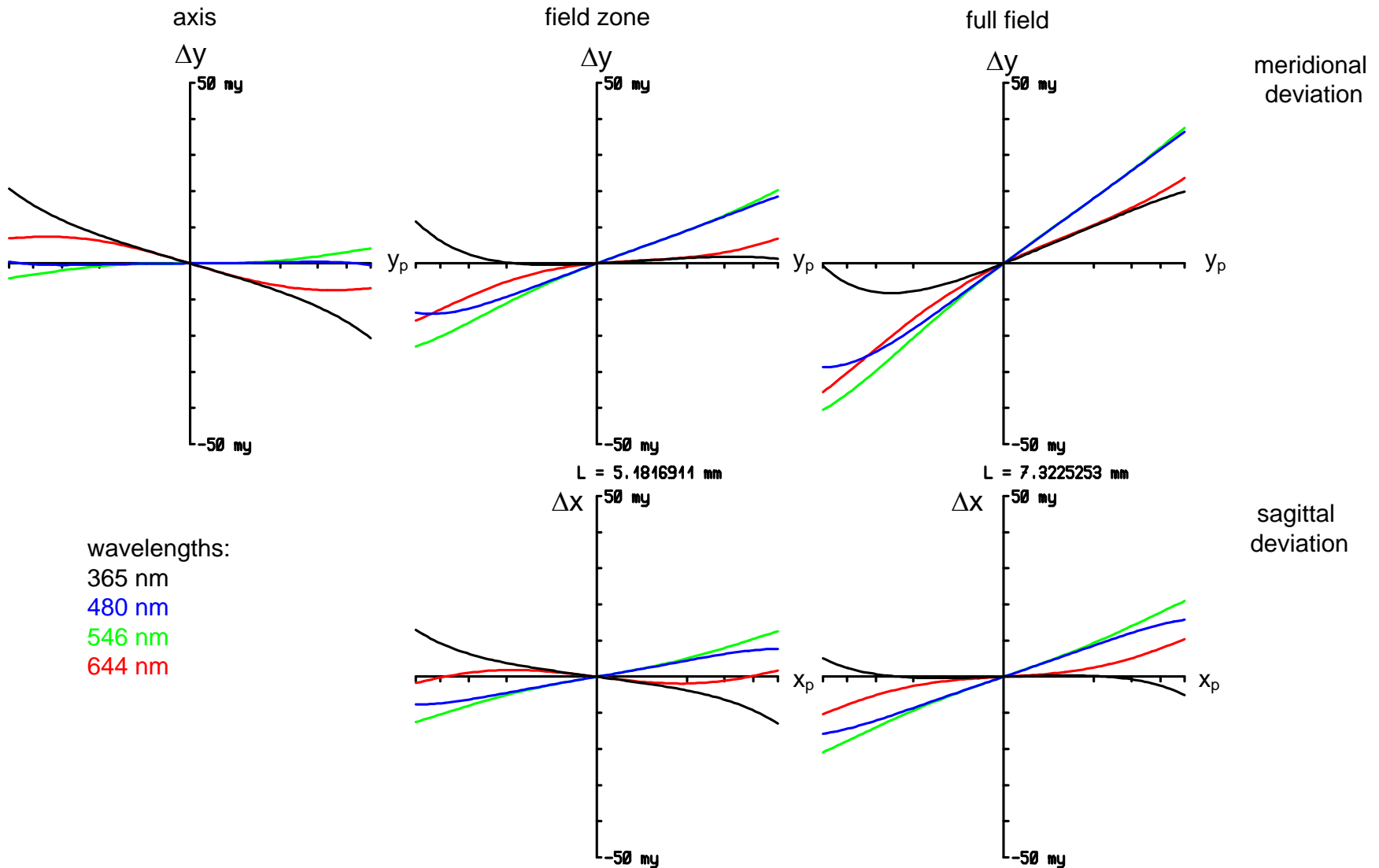


$$\frac{\partial W_{rms}}{\partial \Delta z} = 0 \quad \frac{\partial D_s}{\partial \Delta z} = 0$$

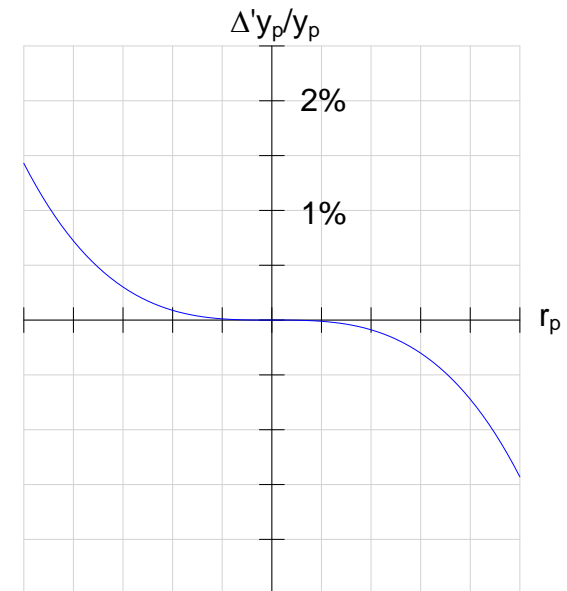
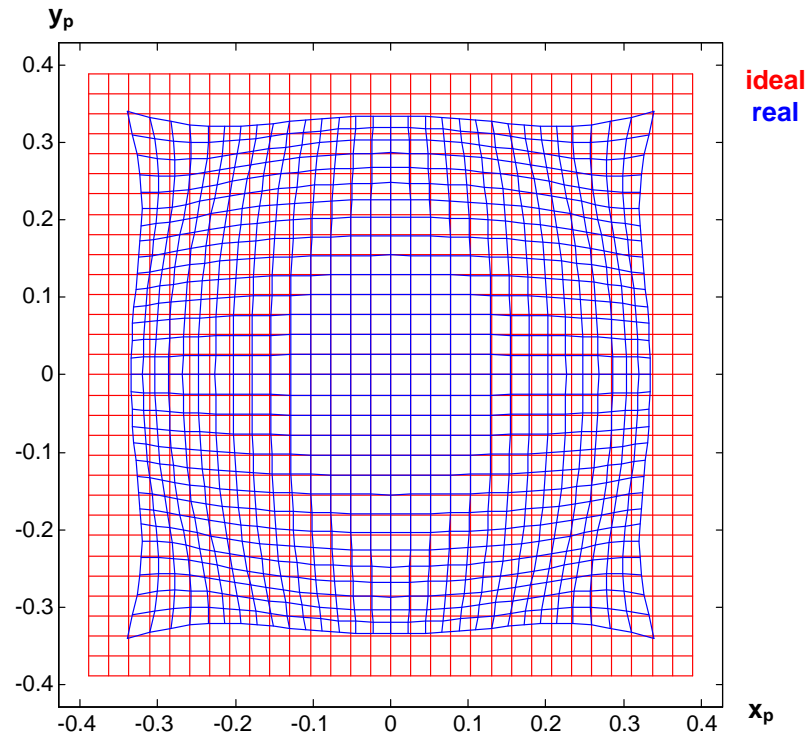


Transverse Aberrations

- Characteristic chart for the representation of transverse aberrations



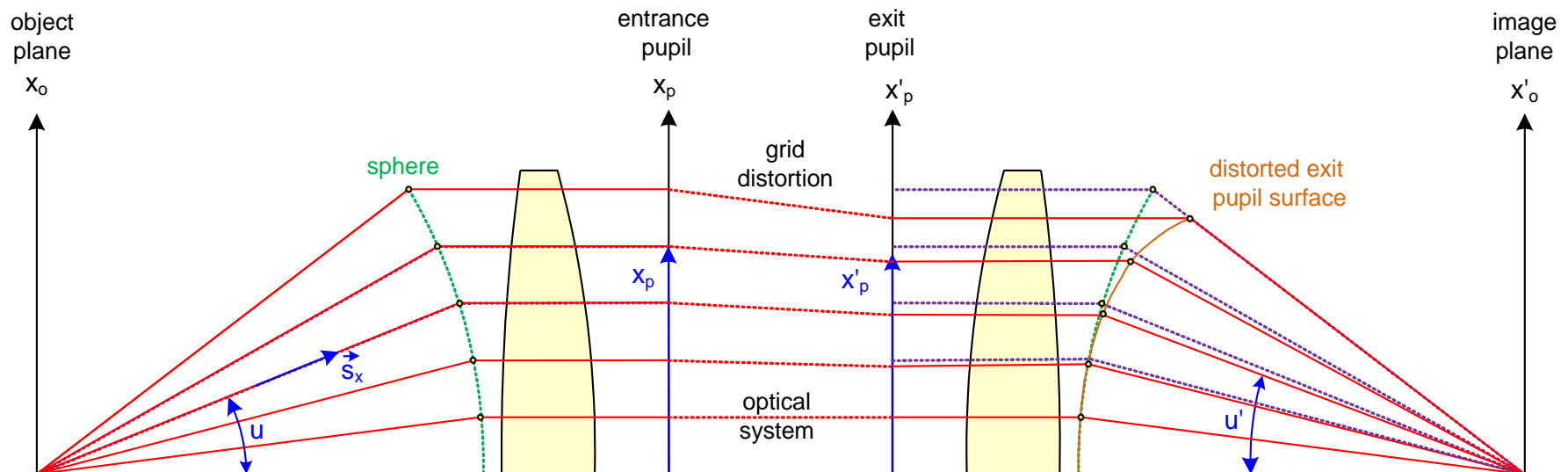
- Characteristic chart for the representation of pupil aberration
- Distortion of the pupil grid from the entrance to the exit pupil
- Pupil aberration can be interpreted as the spherical aberration of the chief ray for the pupil imaging



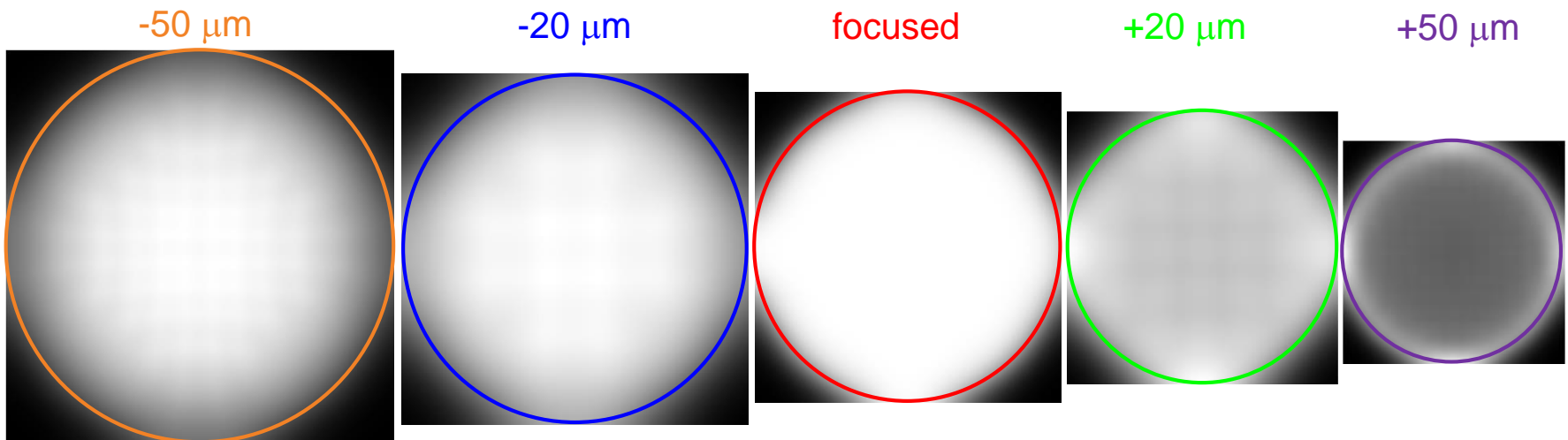
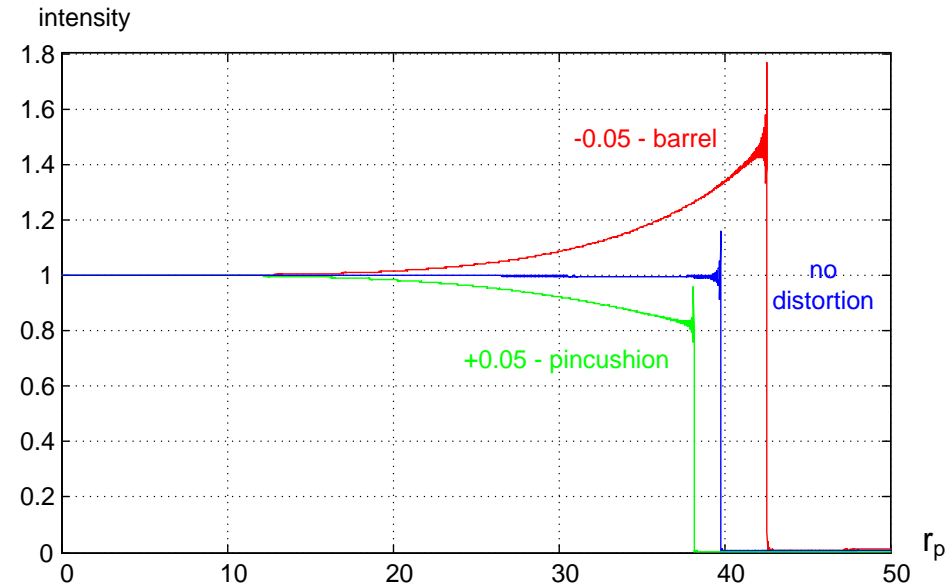
- Sine condition not fulfilled:
 - nonlinear scaling from entrance to exit pupil
 - spatial filtering on warped grid, nonlinear sampling of spatial frequencies
 - pupil size changes
 - apodization due to distortion
 - wave aberration could be calculated wrong
 - quantitative measure of offence against the sine condition (OSC):

distortion of exit pupil grid

$$D_p = \frac{x_{ap}}{f \cdot n \cdot \sin u} - 1$$



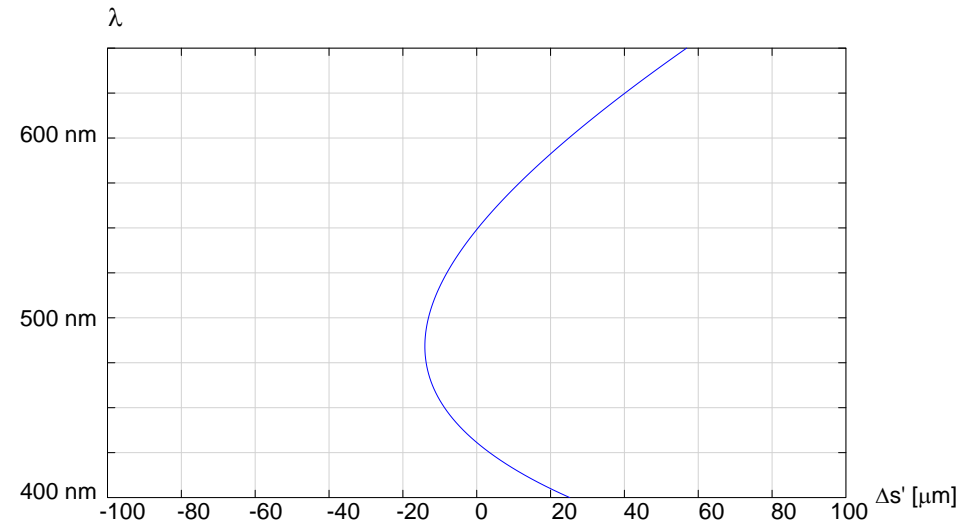
- Photometric effect of pupil distortion: illumination changes at pupil boundary
- Effect induces apodization
- Sign of distortion determines the effect: outer zone of pupil brighter / darker
- Additional effect: absolute diameter of pupil changes



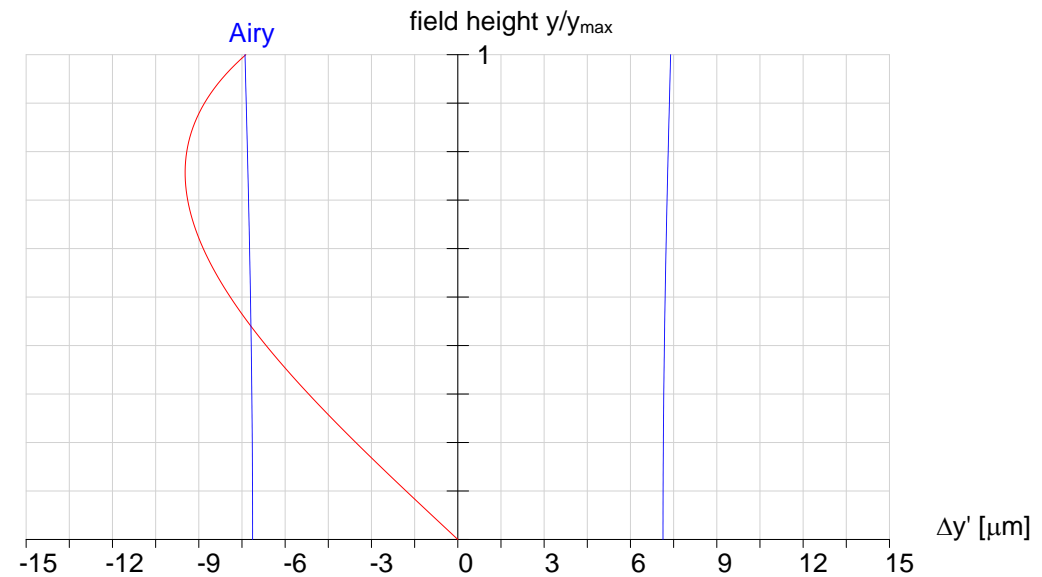


Variation of Chromatical Aberrations

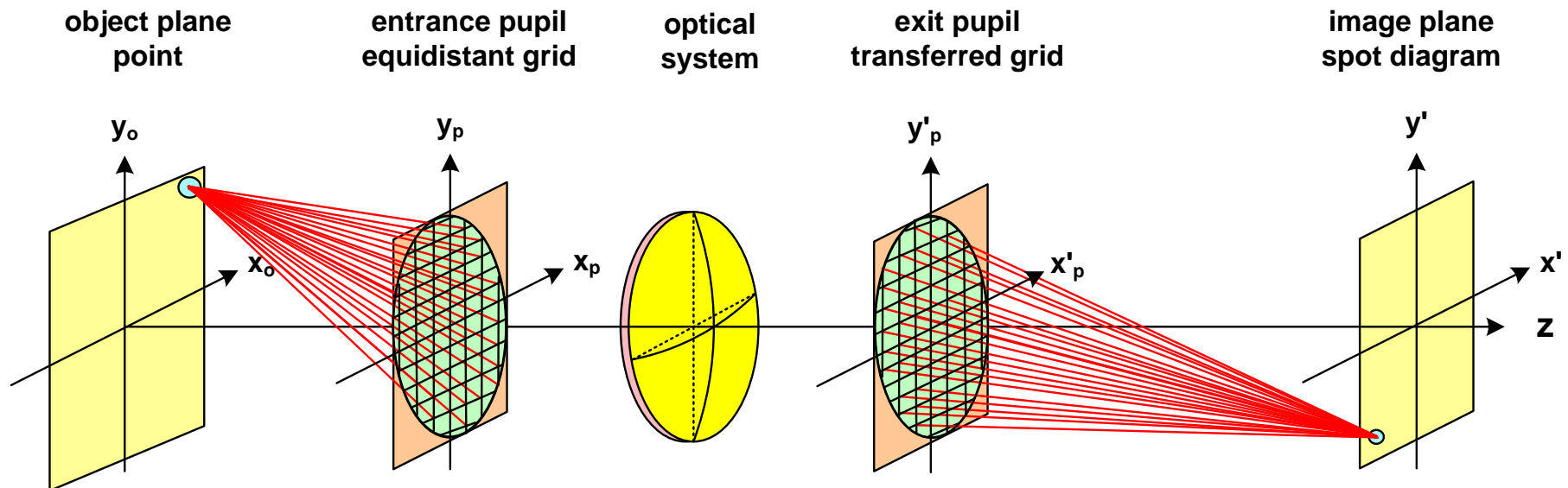
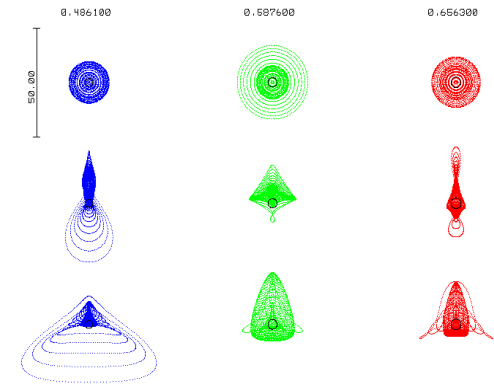
- Representation of the image location as a function of the wavelength
axial chromatical shift



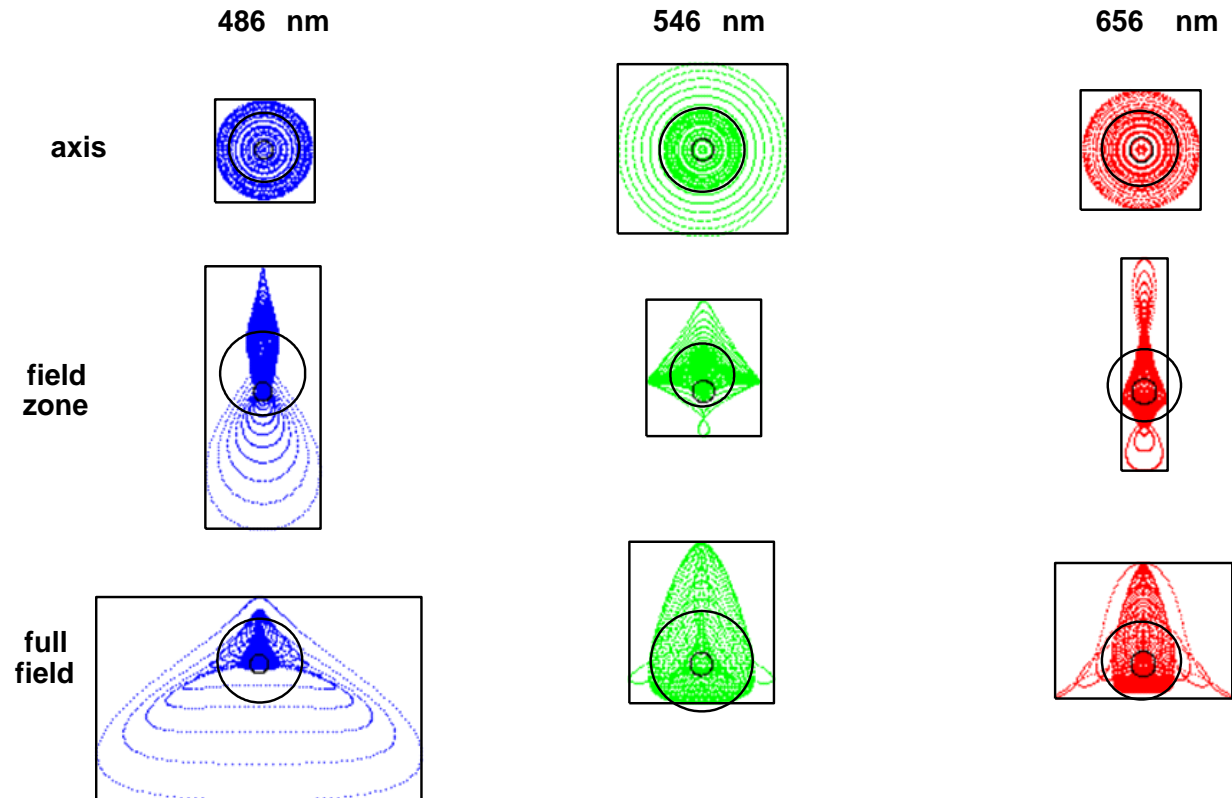
- Representation of the chromatical magnification difference with field height
lateral chromatical aberration



- All rays start in one point in the object plane
- The entrance pupil is sampled equidistant
- In the exit pupil, the transferred grid may be distorted
- In the image plane a spreaded spot diagram is generated



- Variation of field and color
- Scaling of size:
 1. Airy diameter (small circle)
 2. 2nd moment circle (larger circle, scales with wavelength)
 3. surrounding rectangle



- Spot pattern with transverse aberrations Δx_j and Δy_j

1. centroid

$$\langle \Delta x_s \rangle = \frac{1}{N} \sum_j \Delta x_j \quad \langle \Delta y_s \rangle = \frac{1}{N} \sum_j \Delta y_j$$

2. 2nd order moment

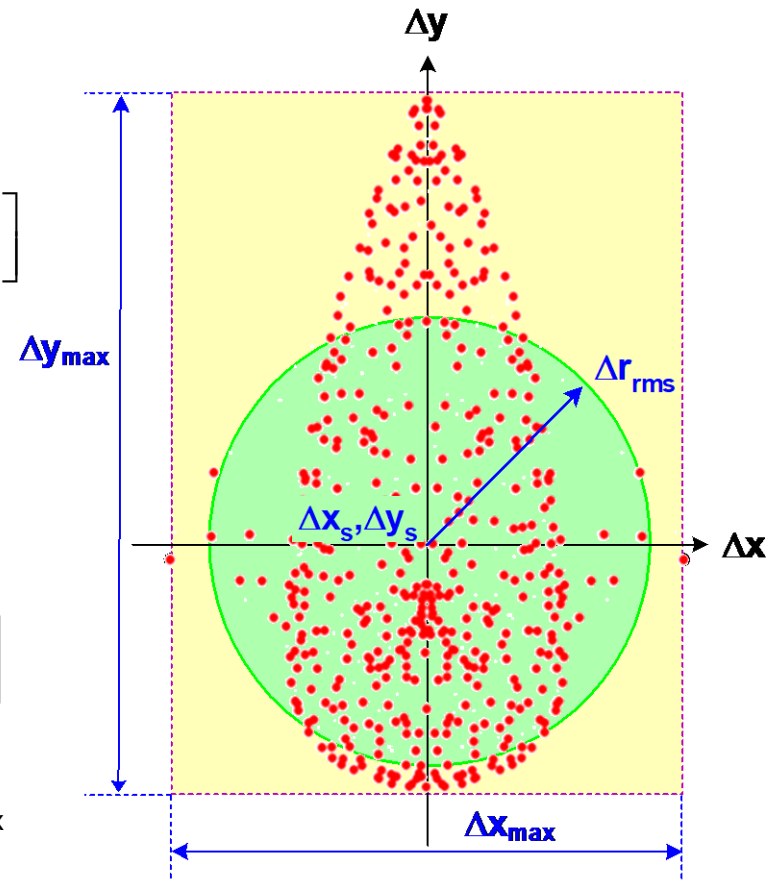
$$M_G = \langle \Delta r^2 \rangle = \frac{1}{N} \sum_j \left[\left(\Delta x_j - \langle \Delta x_s \rangle \right)^2 + \left(\Delta y_j - \langle \Delta y_s \rangle \right)^2 \right]$$

3. diameter $D = 2 \cdot \sqrt{M_G}$

- Generalized:
Rays with weighting factor g_j :
corresponds to apodization

$$M_G = \langle \Delta r^2 \rangle = \frac{1}{N_G} \sum_j g_j \cdot \left[\left(\Delta x_j - \langle \Delta x_s \rangle \right)^2 + \left(\Delta y_j - \langle \Delta y_s \rangle \right)^2 \right]$$

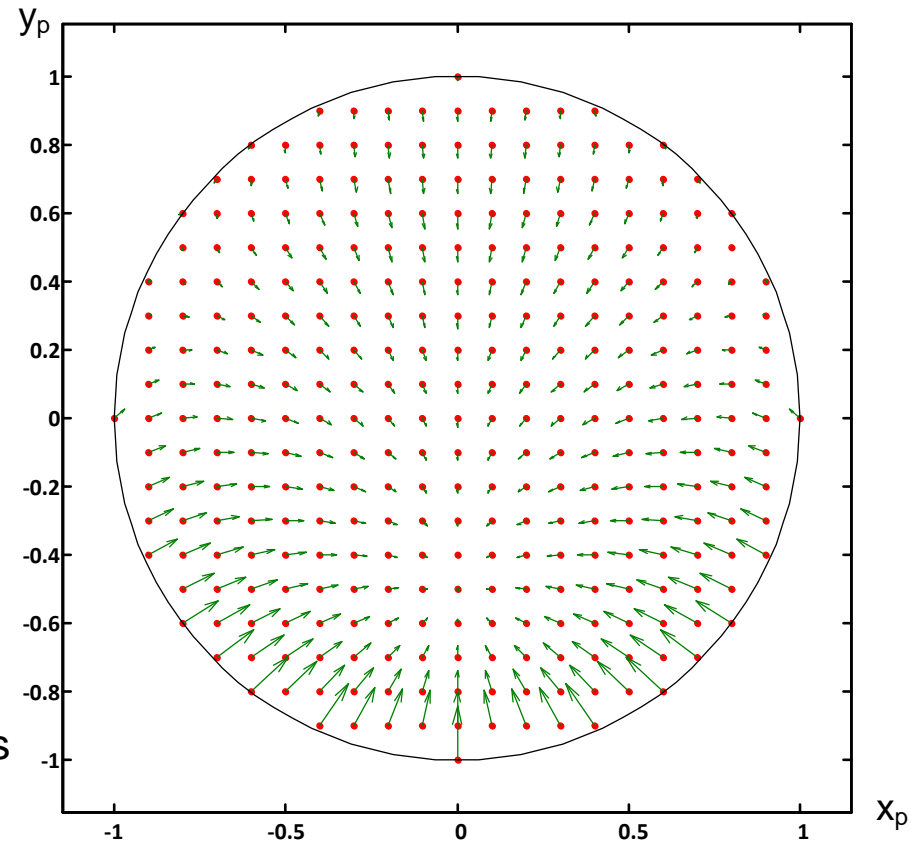
- Worst case estimation:
size of surrounding rectangle $D_x = 2\Delta x_{\max}$, $D_y = 2\Delta y_{\max}$





Kingslakes Diagram

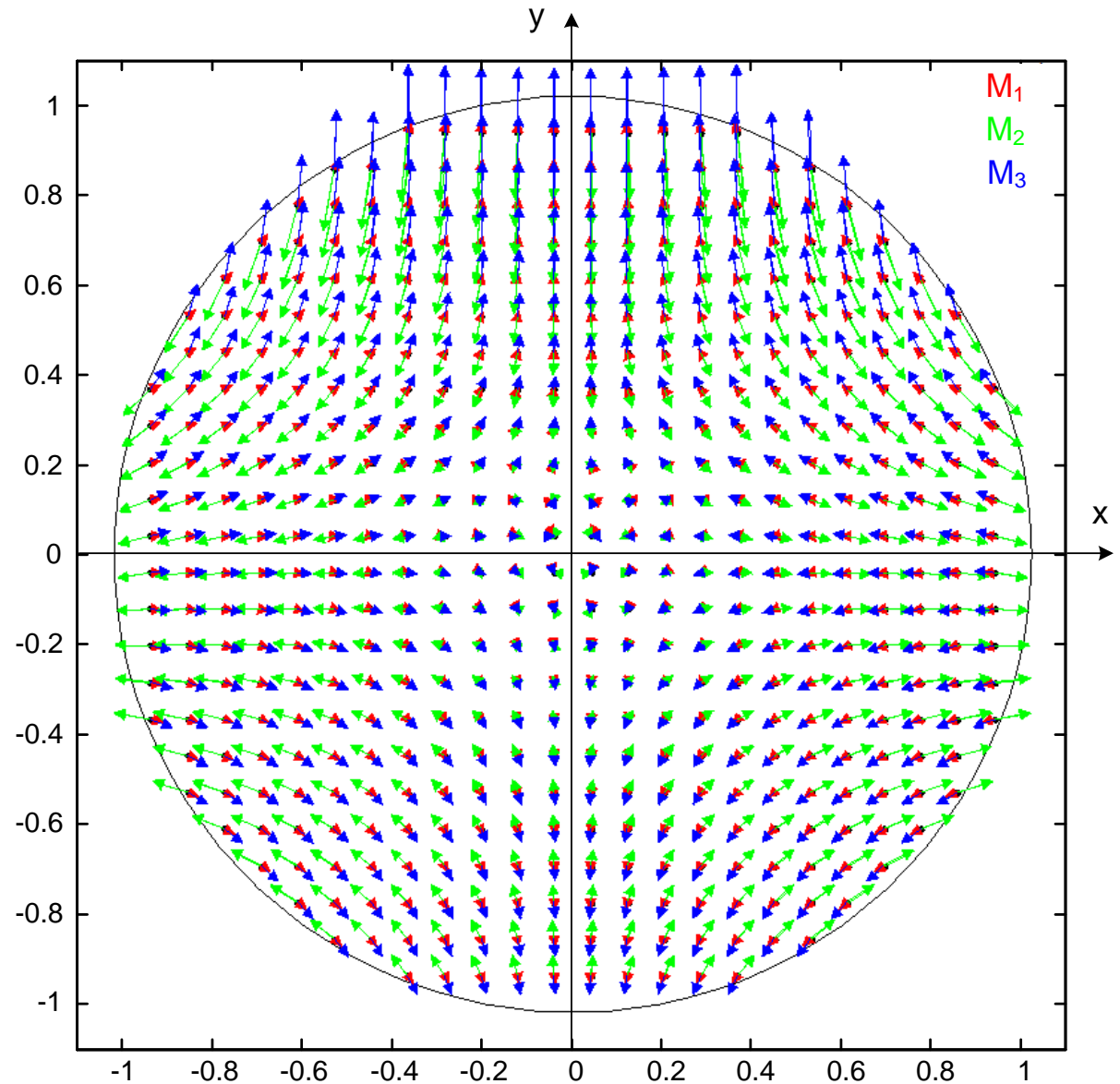
- Practical problem in analysis of classical spot diagrams:
relation between deviations and pupil location is lost
- Idea of Kingslake:
transverse aberrations of spot points drawn in pupil intersection points
- Δx and Δy at every surface in the pupil sampling grid
- Δr at all surfaces in the pupil sampling grid
- Problems:
 1. proper representation of quite different scales
 2. distorted grid in case of induced aberrations





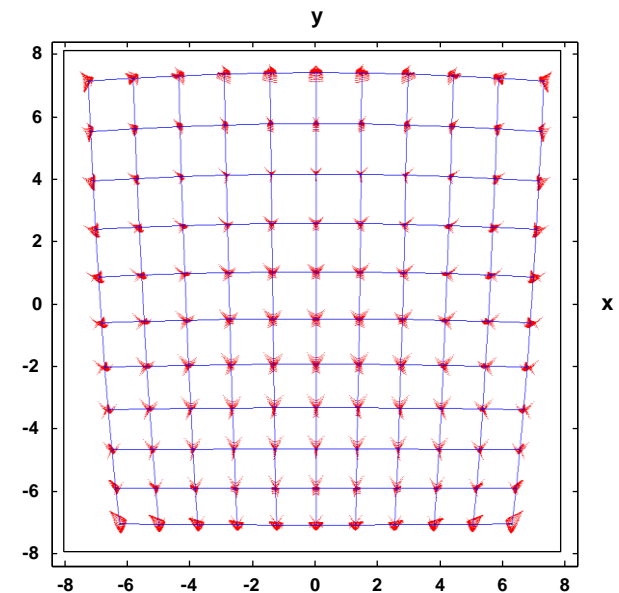
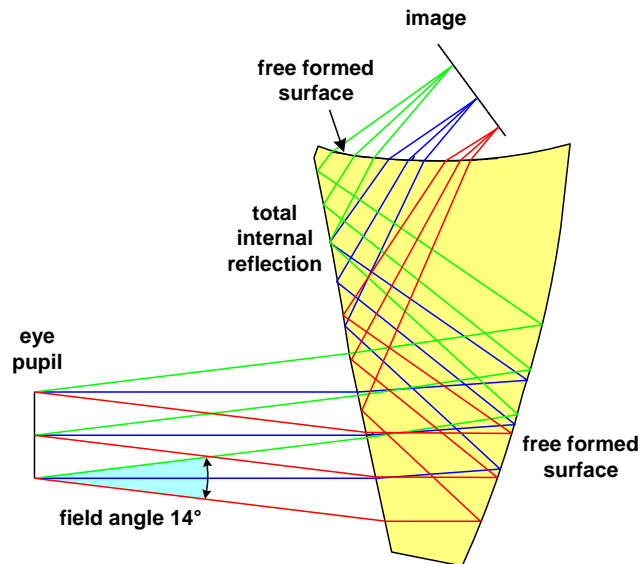
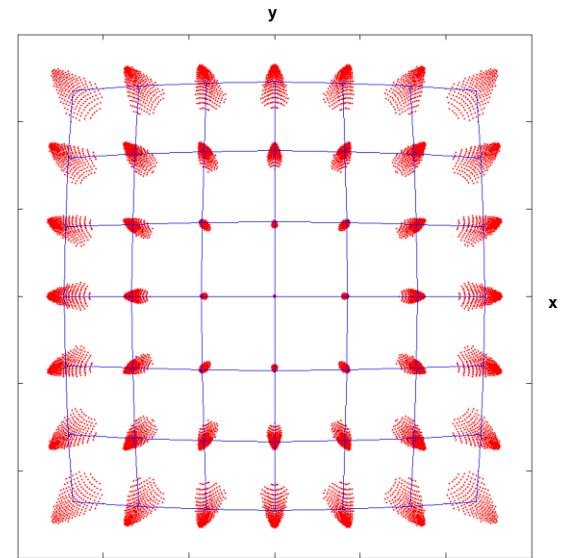
Kingslakes Diagram Extended

- Extension of Kingslakes representation for surface contributions
- Problem: compaction of high complexity, limited clearness



Aberrations of a Single Lens

- Single plane-convex lens,
BK7, $f = 100 \text{ mm}$, $\lambda = 500 \text{ nm}$
 - Spot as a function of field position
 - Coma shape rotates according to circular symmetry
 - Decrease of performance with the distance to the axis
-
- Example HMD without symmetry

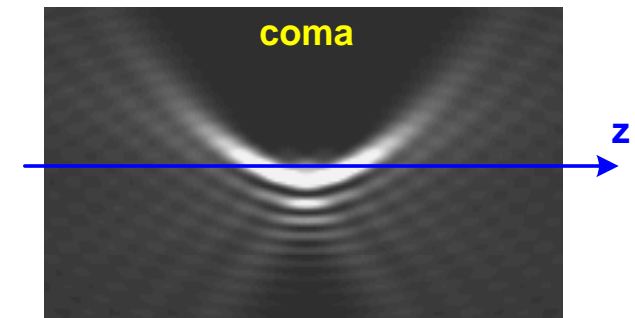
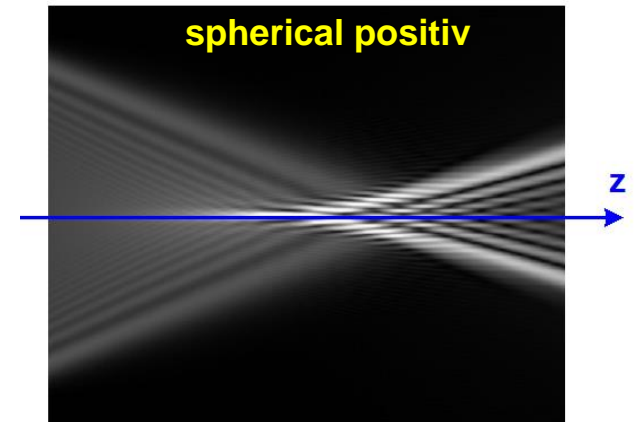
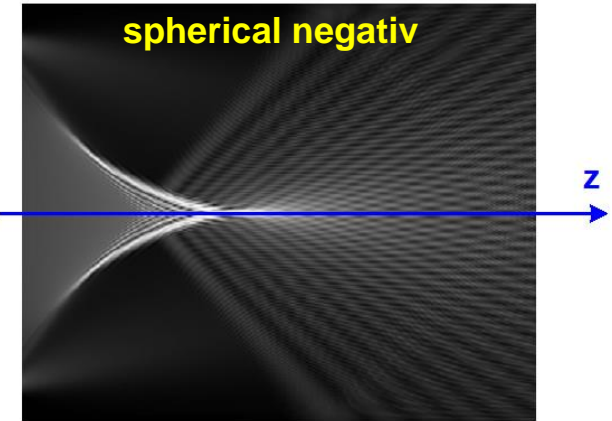


Caustic of Spherical Aberration and Coma

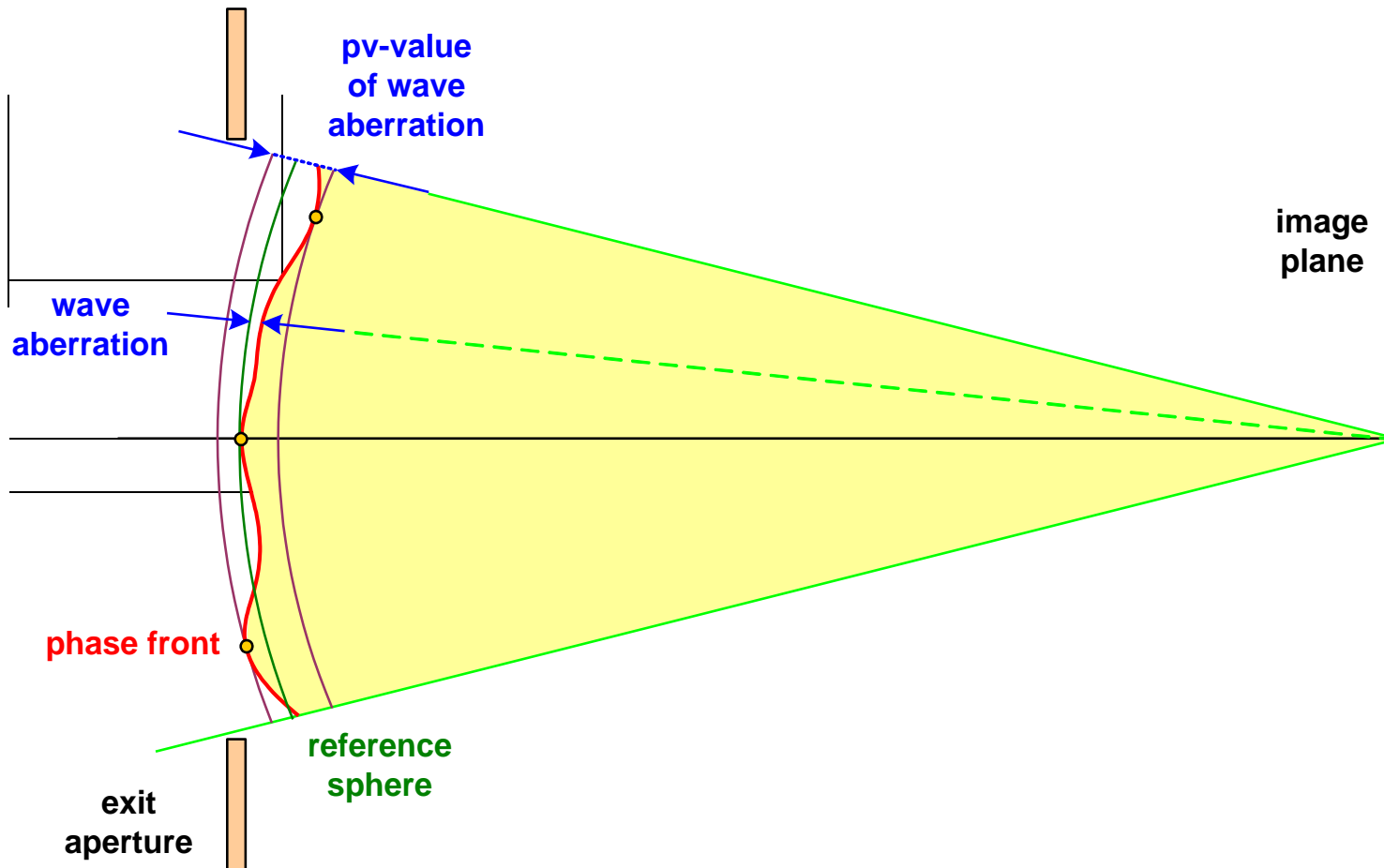
- negativ spherical aberration
intrafocal: compact broadened spot with bright edge
extrafocal: ring structure

- positiv spherical aberration
intrafocal: ring structure with bright center
extrafocal: ring structure with bright outer ring

- coma
bending of caustic
shifted center of gravity



- Definition of the peak valley value





Wave Aberrations

- Classification of wave aberrations for one image point:
Zernike polynomials
- Mean root square of wave front error

$$W_{rms} = \sqrt{\langle W^2 \rangle - \langle W \rangle^2} = \sqrt{\frac{1}{A_{Exp}} \iint [W(x_p, y_p) - W_{mean}(x_p, y_p)]^2 dx_p dy_p}$$

- Normalization: size of pupil area

$$A_{Exp} = \iint dx dy$$

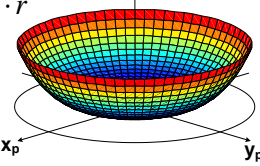
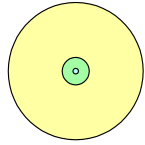
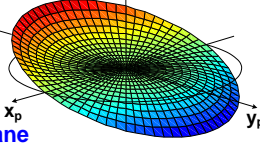
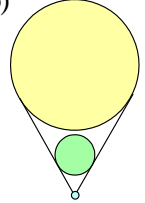
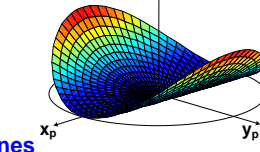

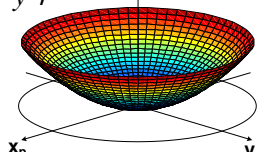
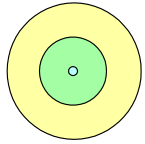
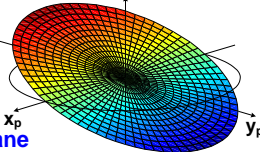

- Worst case / peak-valley wave front error

$$W_{pv} = \max [W_{\max}(x_p, y_p) - W_{\min}(x_p, y_p)]$$

- Generalized for apodized pupils (non-uniform illumination)

$$W_{rms} = \sqrt{\frac{1}{A_{Exp}^{(w)}} \iint I_{Exp}(x_p, y_p) \cdot [W(x_p, y_p) - W_{mean}^{(w)}(x_p, y_p)]^2 dx_p dy_p}$$

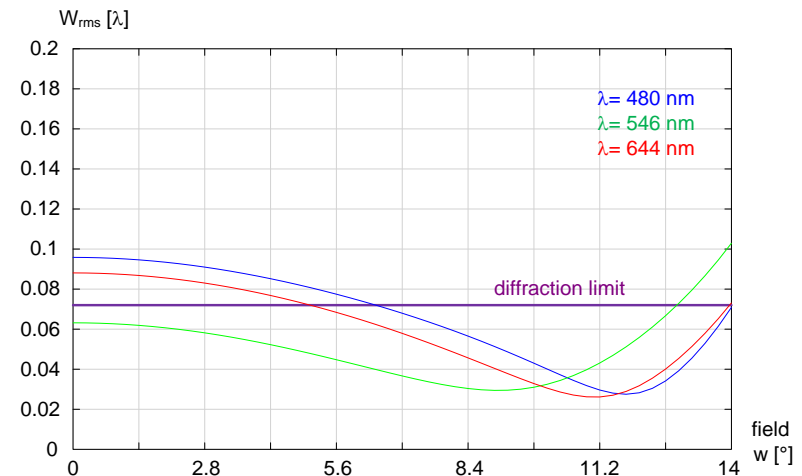
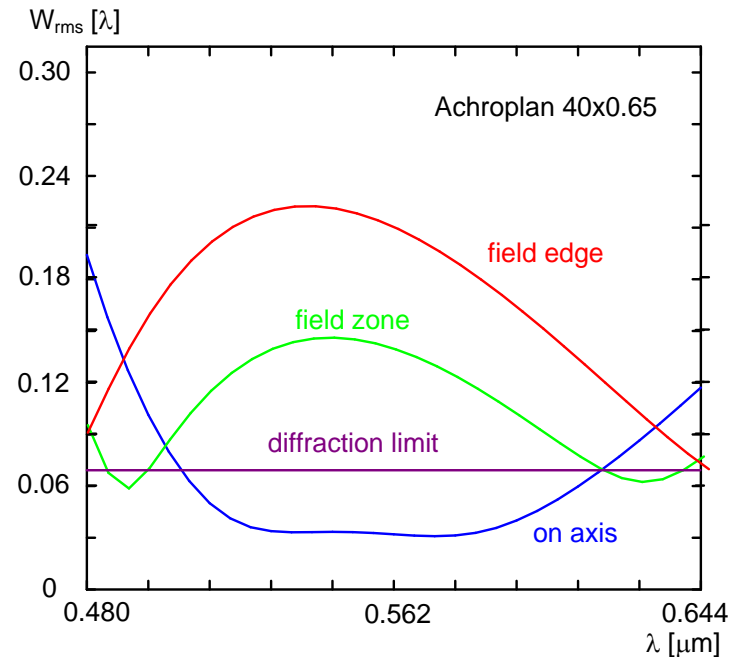
- Relation :
wave / geometrical aberration

Type	Wave aberration	Geometrical spot
Spherical aberration Symmetry to Periodicity	$W = c_1 \cdot r^4$  <p>axis constant</p>	$\Delta x' \propto c_1 \cdot r^3 \sin \varphi$ $\Delta y' \propto c_1 \cdot r^3 \cos \varphi$  <p>point 1 period</p>
Coma Symmetry to Periodicity	$W = c_2 \cdot y r^3 \cos \varphi$  <p>one plane 1 period</p>	$\Delta y' \propto c_2 \cdot y r^2 \cdot (2 + \cos 2\varphi)$ $\Delta x' \propto c_2 \cdot y r^2 \sin 2\varphi$  <p>one straight line 2 periods</p>
Astigmatism Symmetry to Periodicity	$W = c_3 \cdot y^2 r^2 \cos^2 \varphi$  <p>two planes 2 period</p>	$\Delta x' = 0$ $\Delta y' \propto c_3 \cdot y^2 r \cos \varphi$  <p>two straight lines 1 period</p>
Field curvature (sagittal) Symmetry to Periodicity	$W = c_4 \cdot y^2 r^2$  <p>axis constant</p>	$\Delta x' \propto c_4 \cdot y^2 r \sin \varphi$ $\Delta y' \propto c_4 \cdot y^2 r \cos \varphi$  <p>point 1 period</p>
Distortion Symmetry to Periodicity	$W = c_5 \cdot y^3 r \cos \varphi$  <p>one plane 1 period</p>	$\Delta x' = 0$ $\Delta y' \propto c_5 \cdot y^3$  <p>one straight line constant</p>



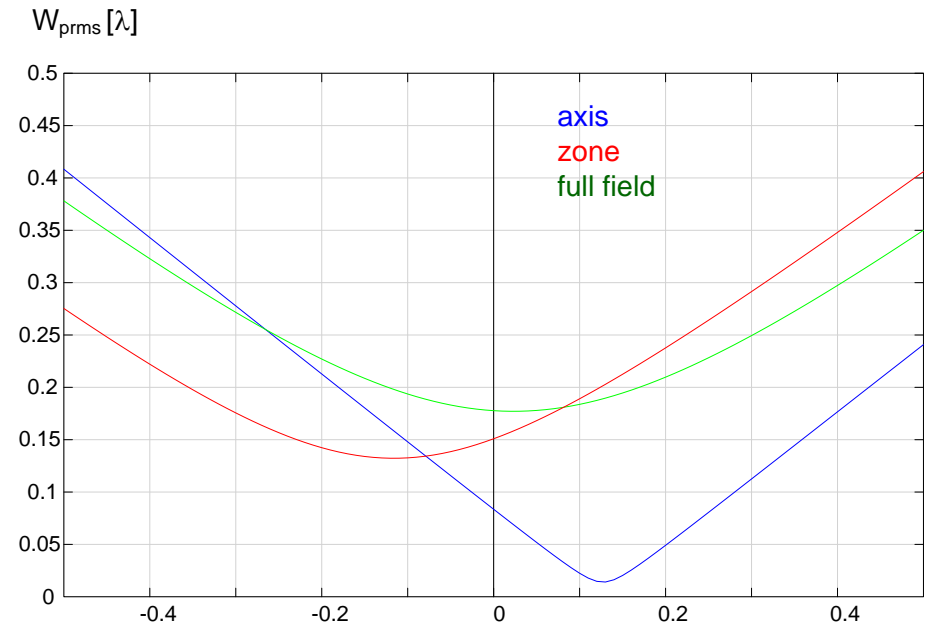
Typical Variation of Wave Aberrations

- Microscopic objective lens:
Changes of rms value of wave aberration with wavelength
- Common practice:
 1. diffraction limited on axis for main part of the spectrum
 2. Requirements relaxed in the outer field region
 3. Requirement relaxed at the blue edge of the spectrum
- Representation of the wave aberration with field position

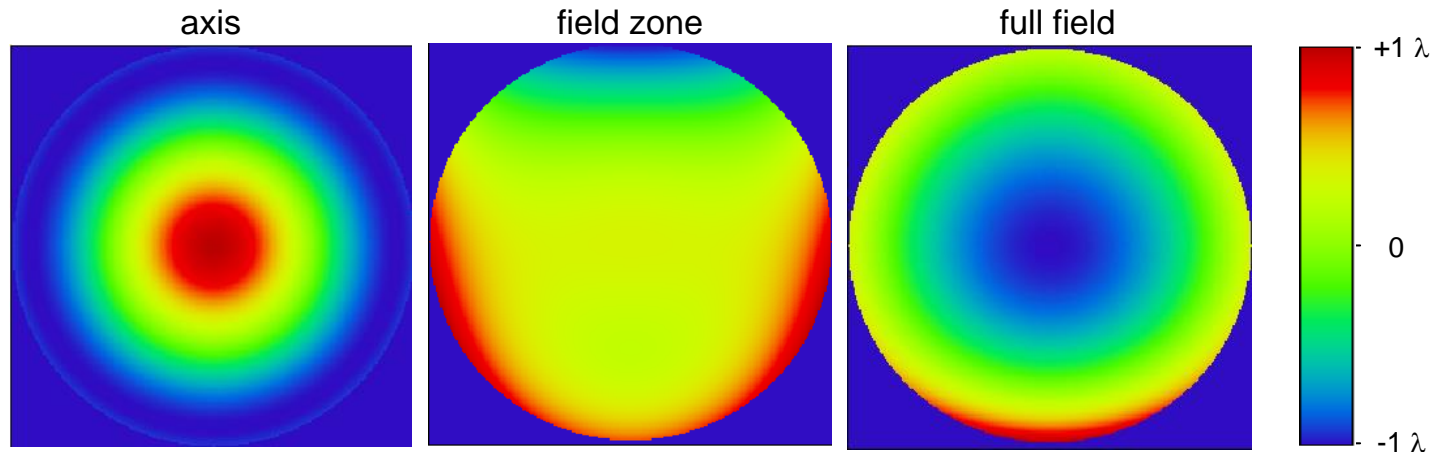


Typical Variation of Wave Aberrations

- Representation of the wave aberration for defocussing at several field points
 - decrease of performance with field height
 - field curvature

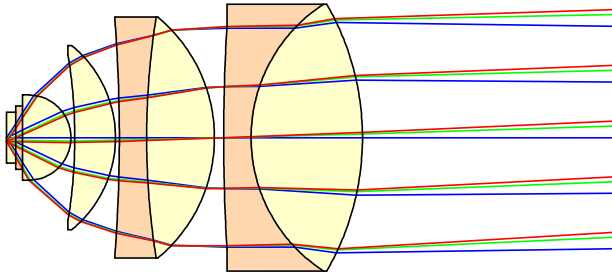


- Wavefront over the pupil as surface

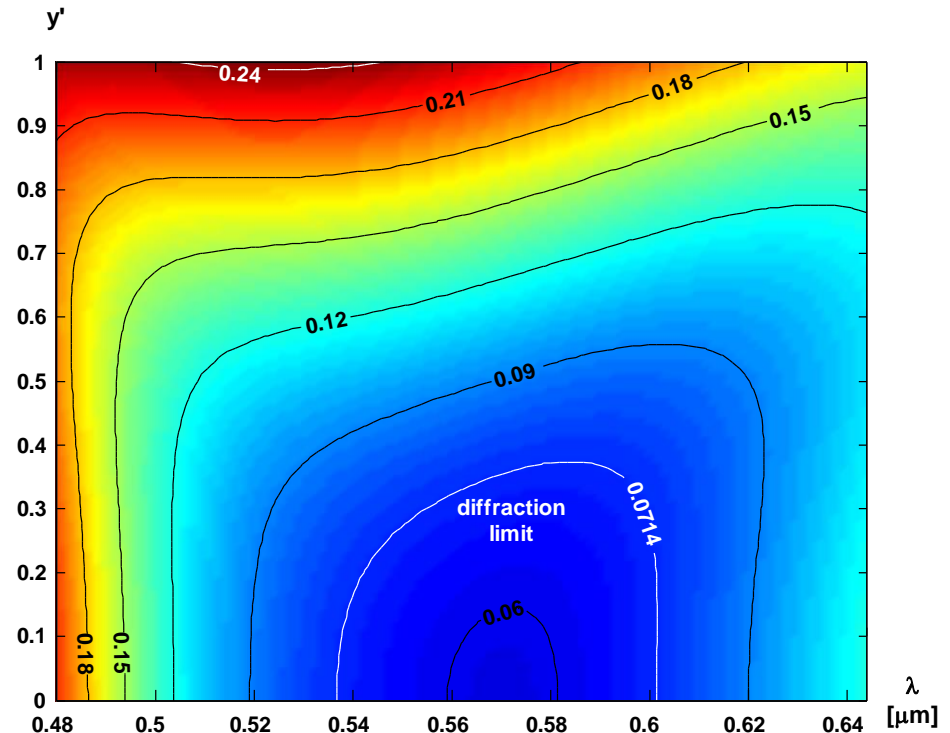


Typical Variation of Wave Aberrations

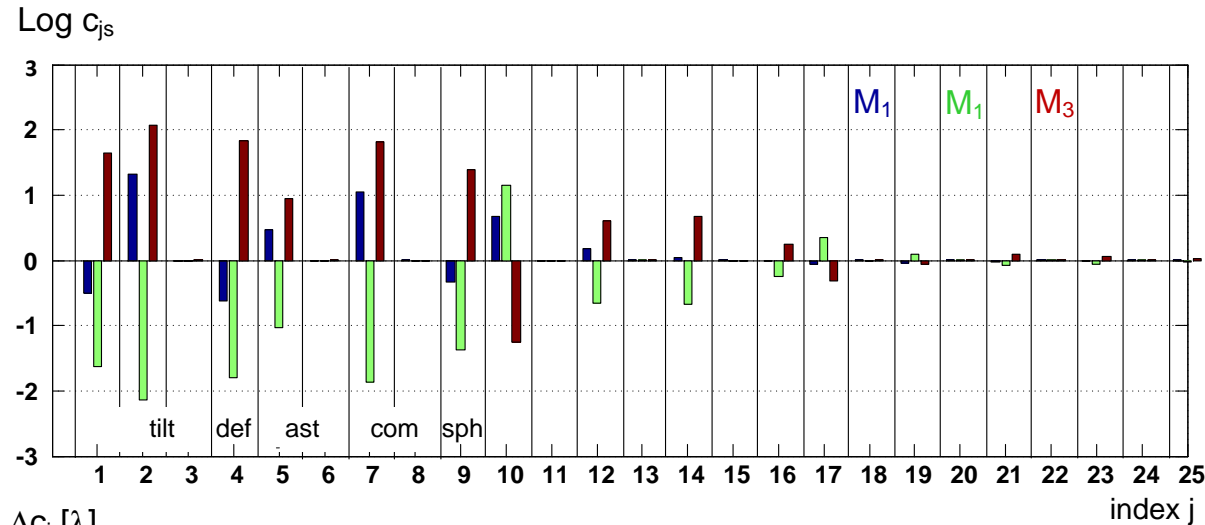
- Representation of the wave aberration as a function of field and wavelength for a microscopic lens



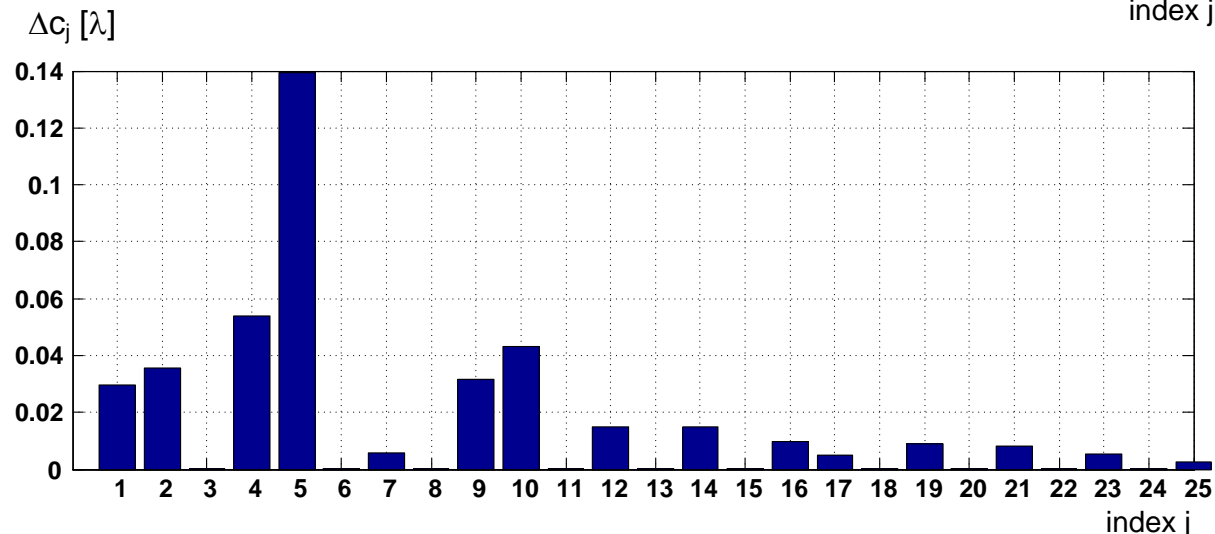
- Analysis:
 1. diffraction limited correction near to axis for medium wavelength range
 2. no flattening
 3. blue edge more critical than red edge



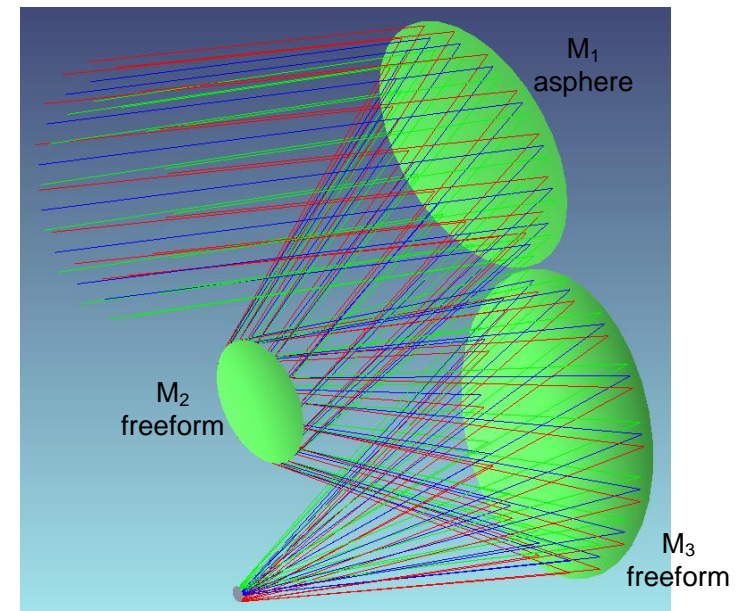
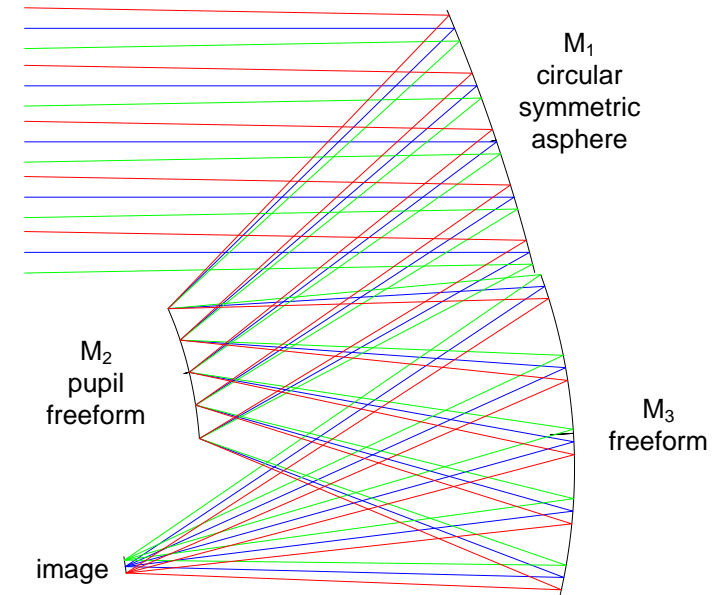
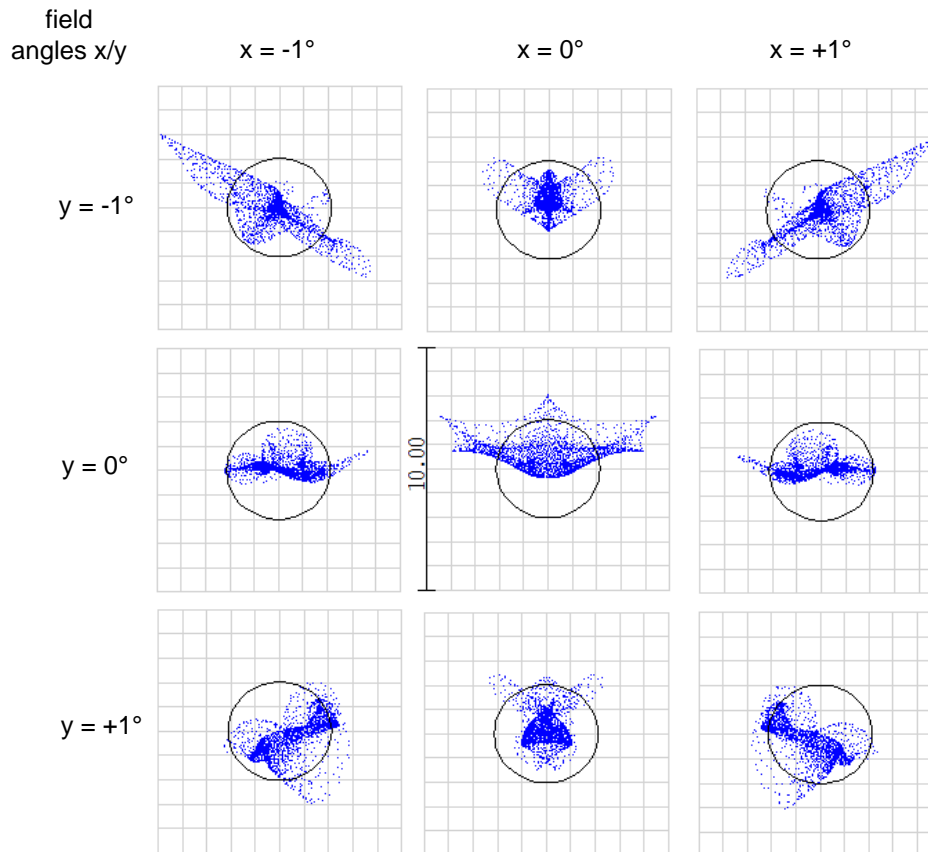
- Contributions of the lower Zernike coefficients per surface,
In logarithmic scale not additive
(Fringe convention)



- Error in additivity due to numerical reasons for astigmatism
- Effect of induced aberrations and grid distortion in the range of $\lambda / 20$ in this case

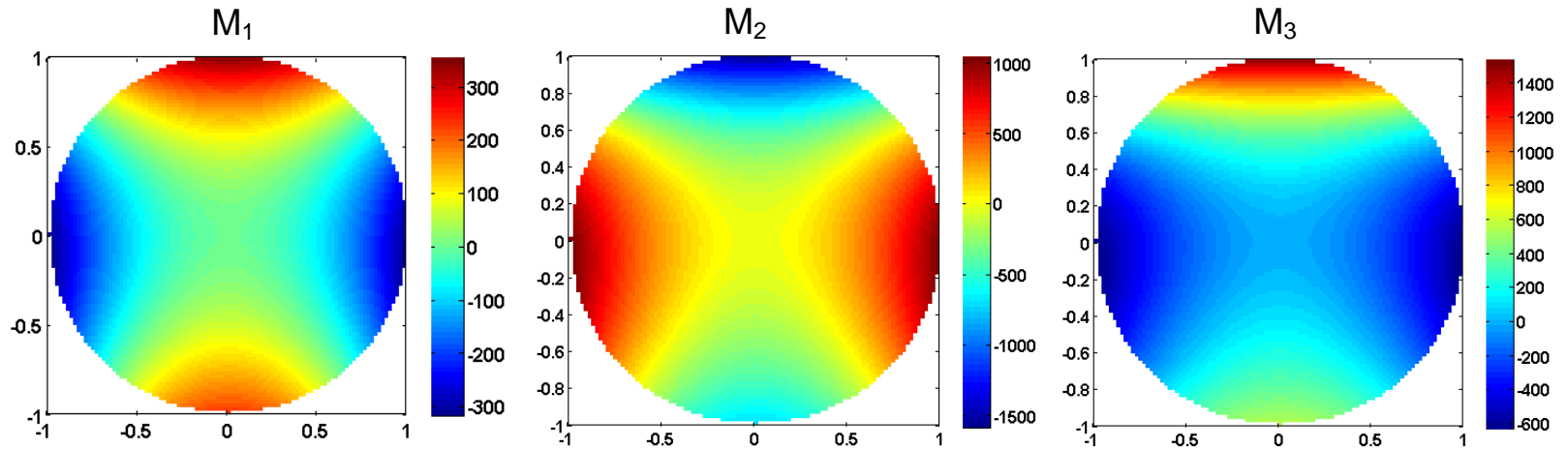


- Example system: plane symmetric TMA system
nearly diffraction limited correction for a small field of view
 M_1 : off axis asphere, M_2 , M_3 : freeforms
- F-number 1.8, field $-1^\circ \dots +1^\circ$



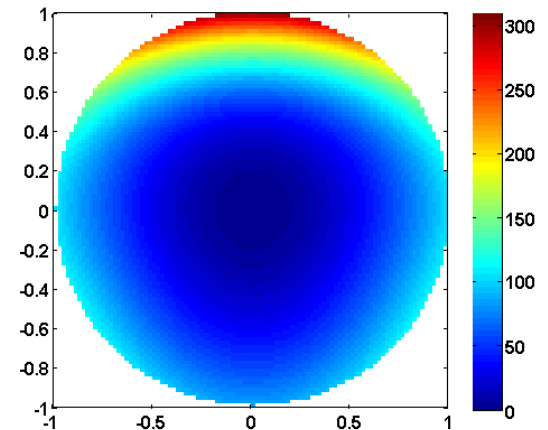
Wavefront Contribution of every Surface

- Surface contributions of every mirror with parabolal reference pupil rescaling neglected



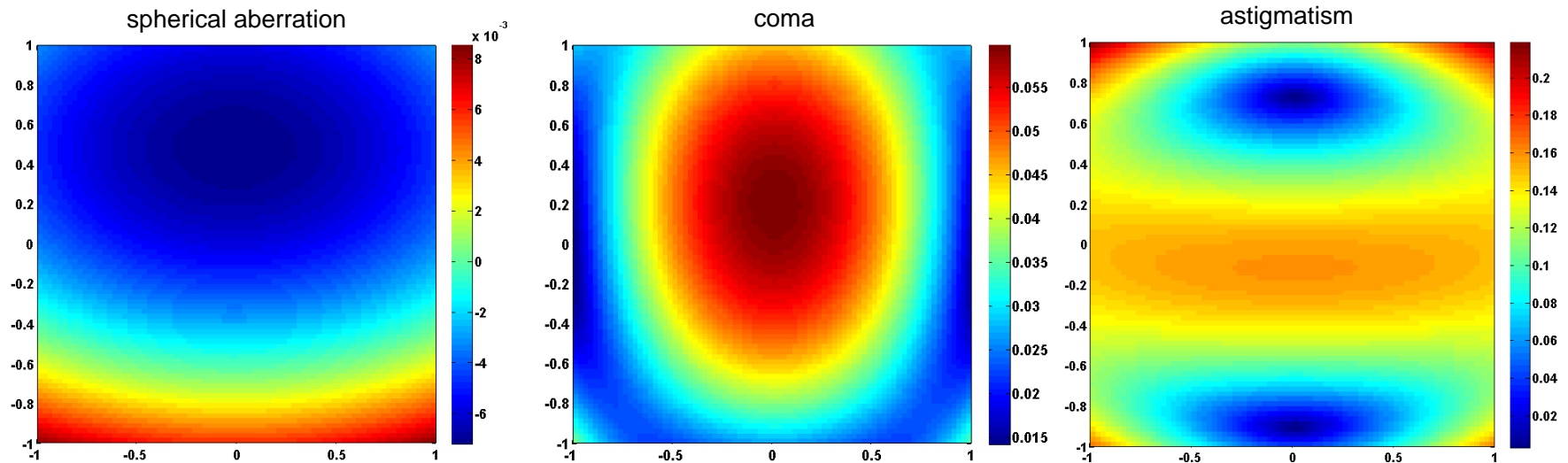
- Dominating astigmatism
- Sum of wave aberration not additive, difference due to induced aberrations

sum of surface contributions



Zernikes as Function of the Field

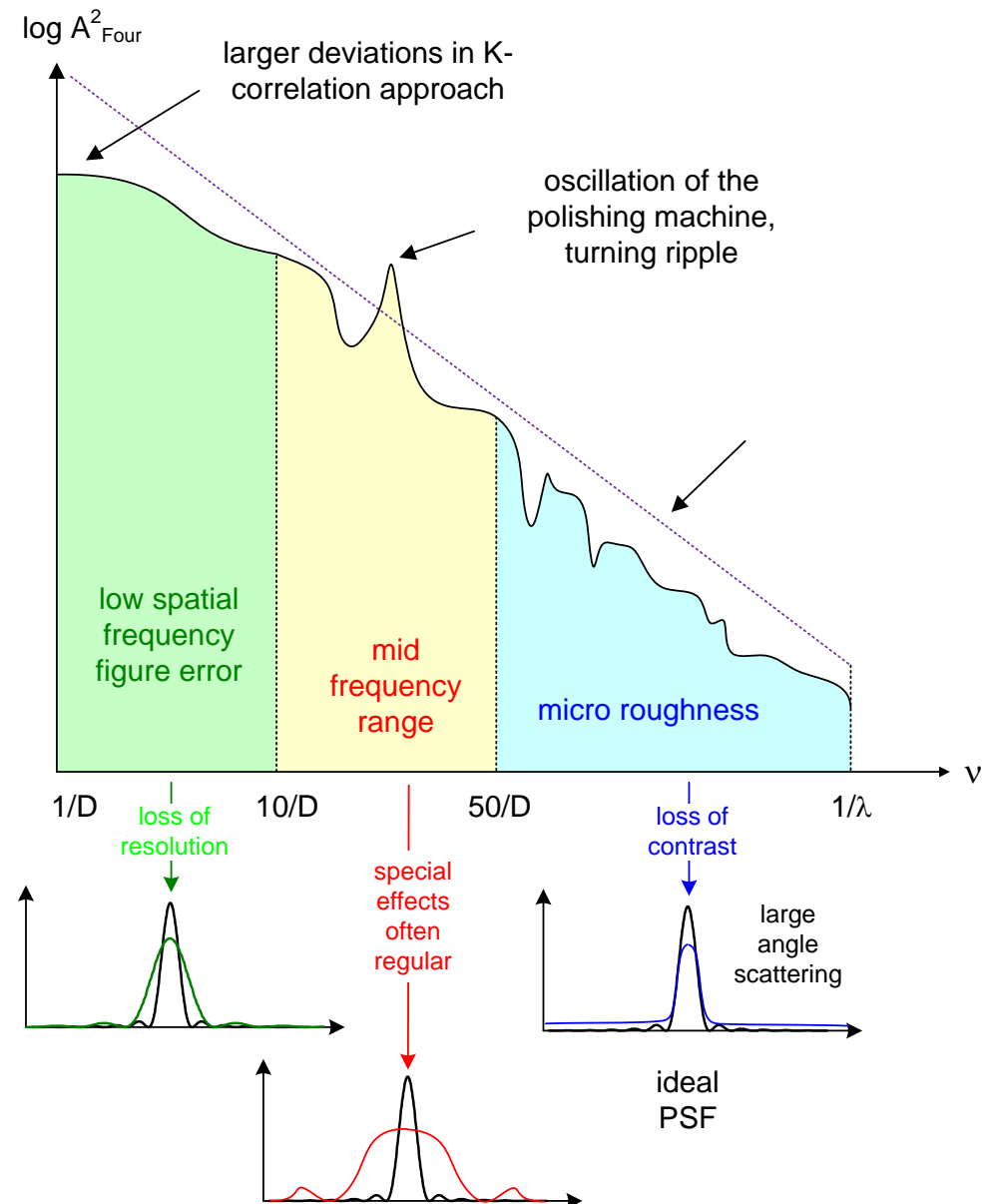
- Low order Zernikes as a function of the field position



- Completely different distributions,
Complete characterization gives a huge amount of detailed information.
- Also analytical solution for lower orders provided in the literature

R. Gray, C. Dunn, K. Thompson, J. Rolland, Opt. Express 20(2012) p. 16436, An analytic expression for the field dependence of Zernike polynomials in rotational symmetric optical systems

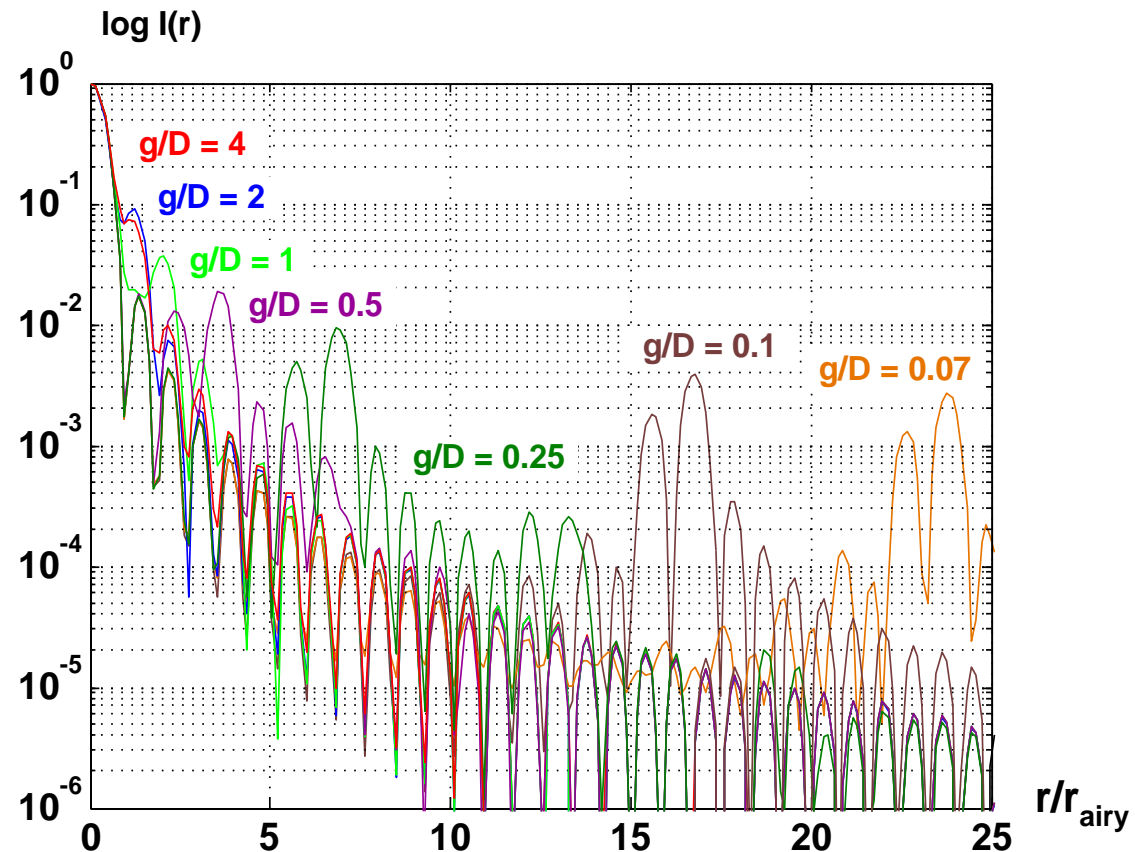
- Typical impact of spatial frequency ranges on PSF
- Low frequencies: loss of resolution
classical Zernike range
- High frequencies: Loss of contrast
statistical
- Large angle scattering
- Mid spatial frequencies: complicated, often structured false light distributions





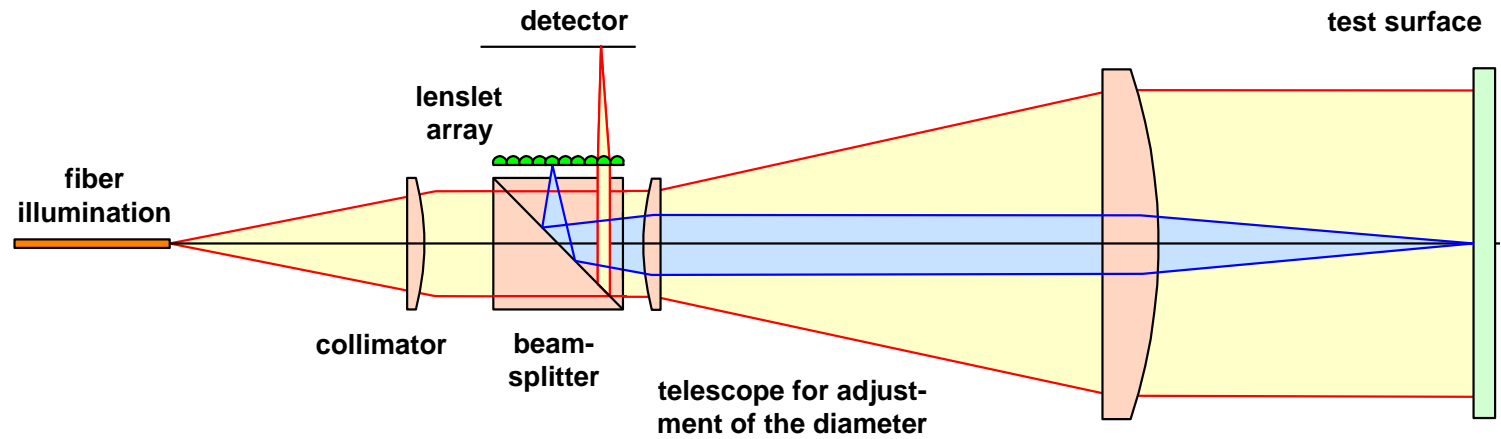
Spatial Frequency of Wavefront Aberrations

- The spatial frequency determines the effect of the wave front aberration
- Characteristic ranges, scaled on the diameter of the pupil:
 - figure error : Zernike
causes resolution loss
 - midfrequency range
 - high frequency : roughness
causes contrast loss

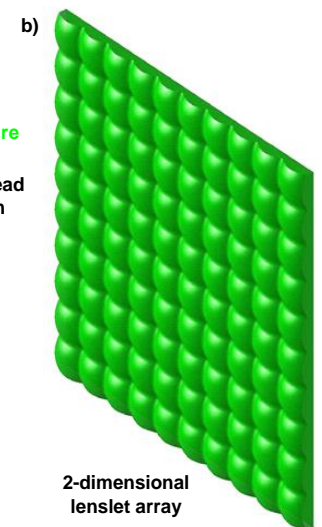
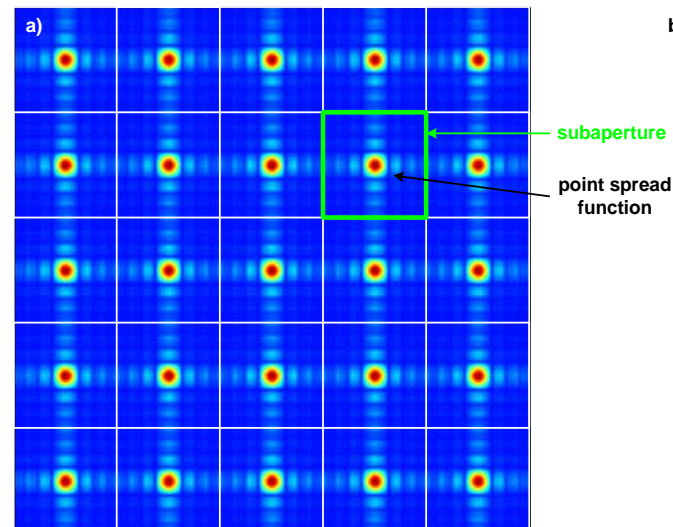
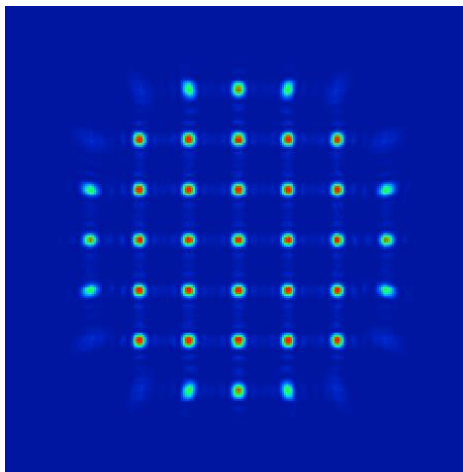


Hartmann Shack Wavefront Sensor

- Typical setup for component testing



- Lenslet array

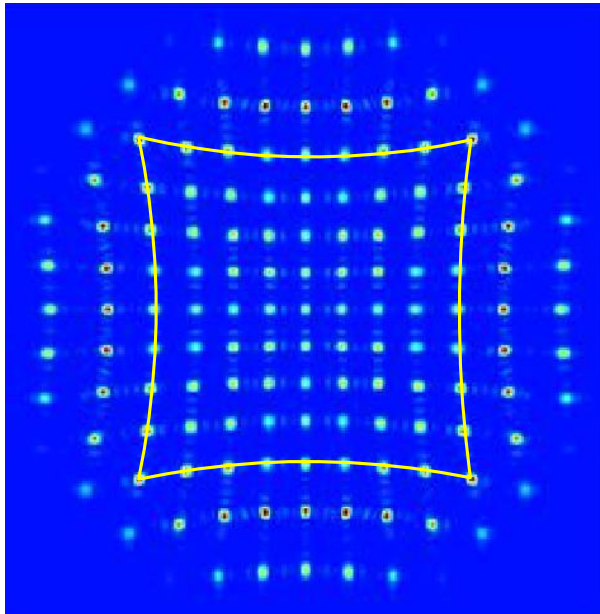


Spot Pattern of a HS - WFS

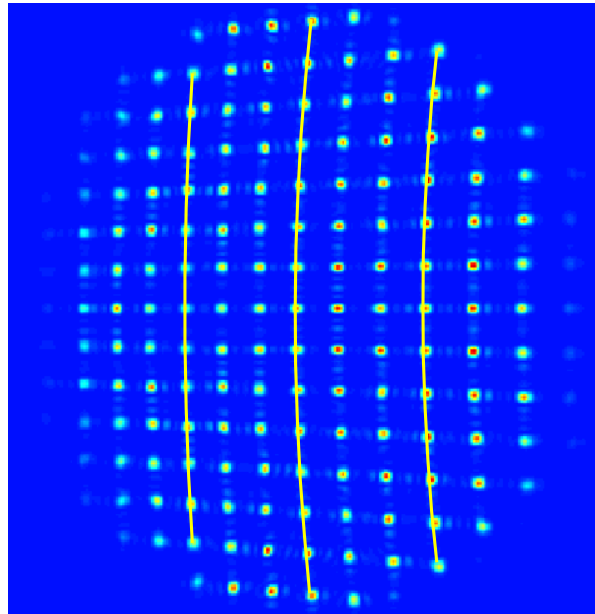


- Aberrations produce a distorted spot pattern
- Calibration of the setup for intrinsic residual errors
- Problem: correspondence of the spots to the subapertures

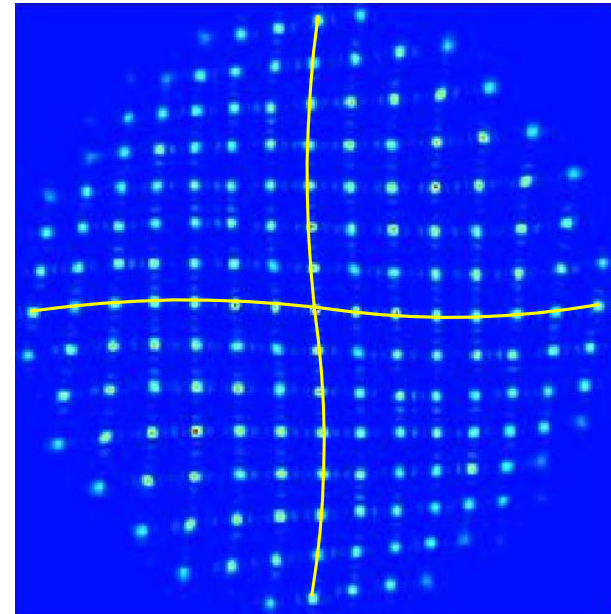
a) spherical aberration



b) coma

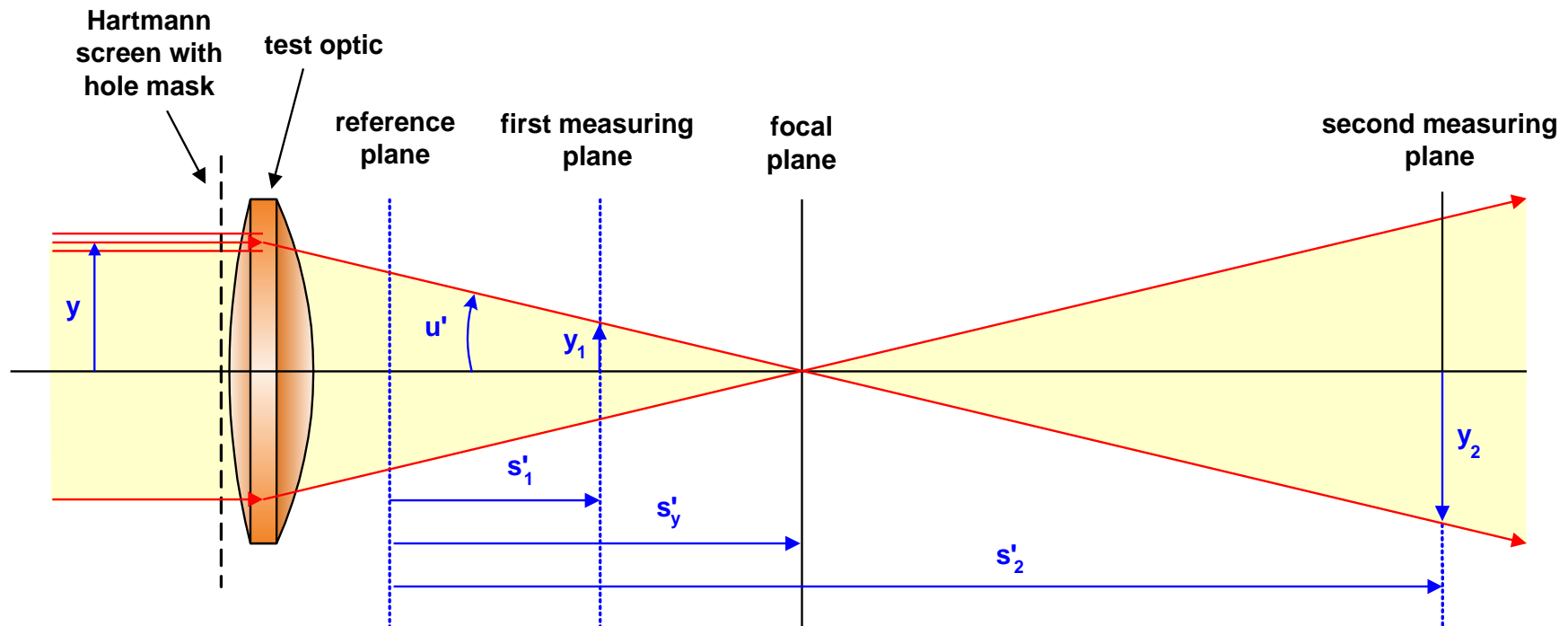


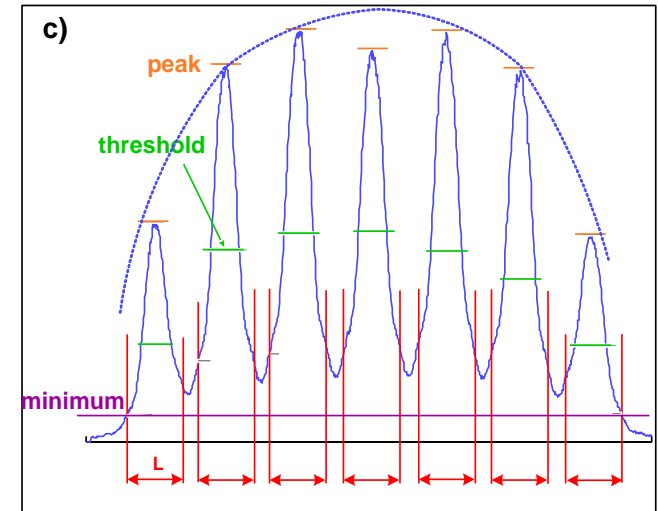
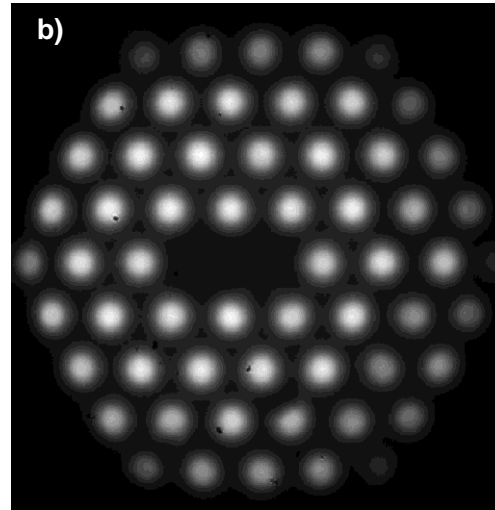
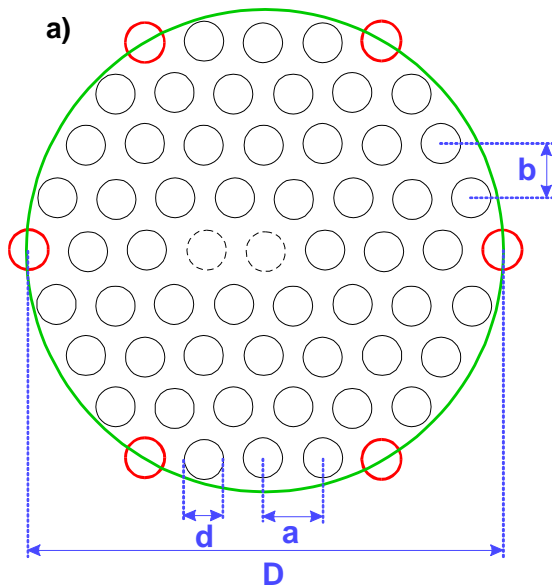
c) trefoil aberration



- Similar to Hartmann Shack Method with simple hole mask and two measuring planes
- Measurement of spot center position as geometrical transverse aberrations
- Problems: broadening by diffraction

$$s'_y = s'_1 + (s'_2 - s'_1) \cdot \frac{y_1}{y_1 + y_2}$$



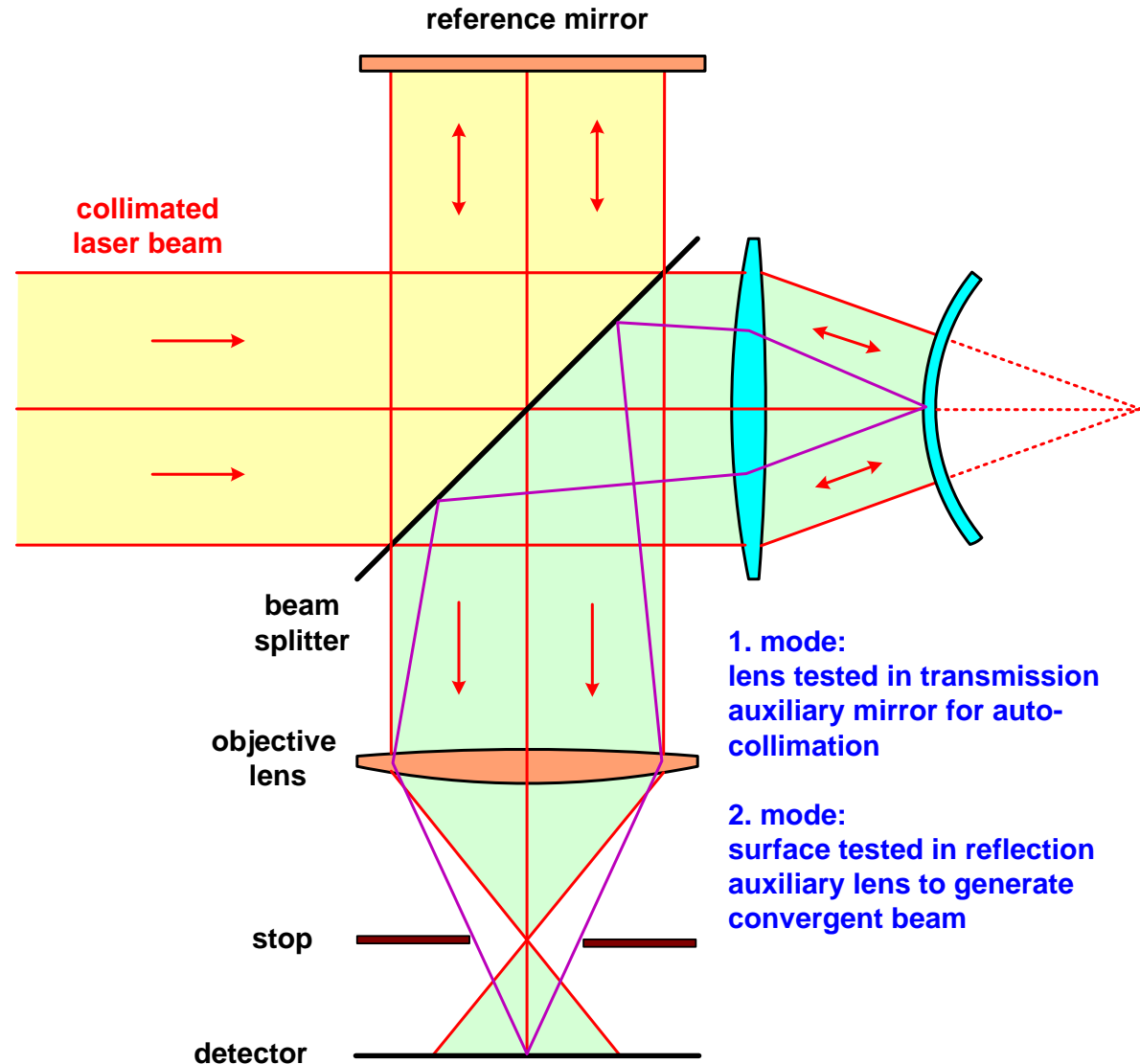


- Real pinhole pattern with signal
- Problems with cross talk and threshold

Testing with Twyman-Green Interferometer



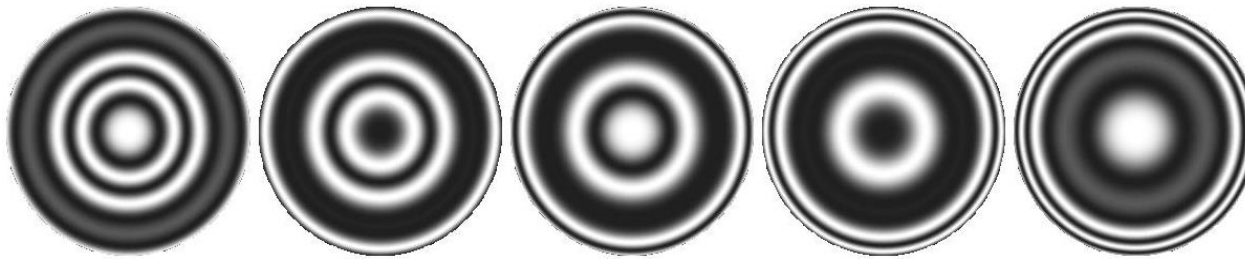
- Short common path, sensible setup
- Two different operation modes for reflection or transmission
- Always factor of 2 between detected wave and component under test



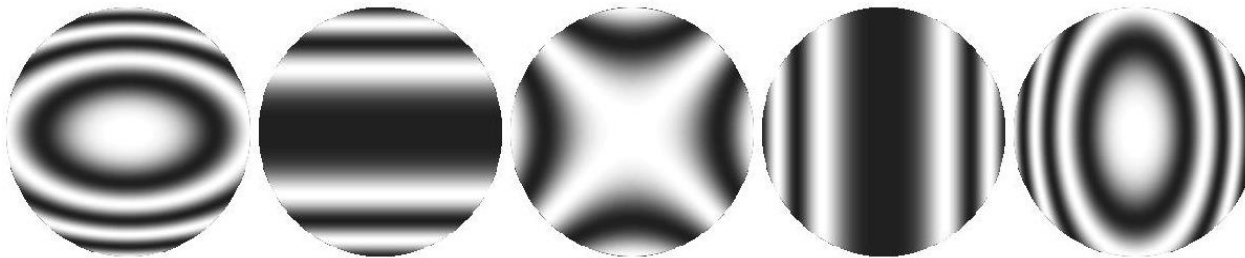


Interferograms of Primary Aberrations

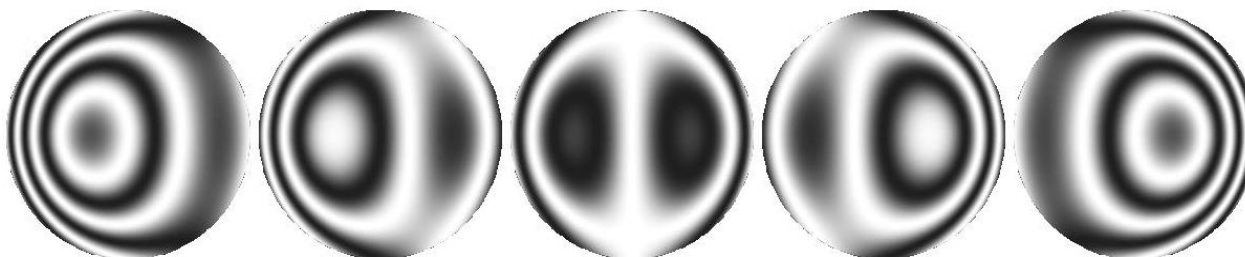
Spherical aberration 1λ



Astigmatism 1λ



Coma 1λ



-1

-0.5

0

+0.5

+1

Defocussing in λ

Interferogram - Definition of Boundary

- Critical definition of the interferogram boundary and the Zernike normalization radius in reality

