Design and Correction of Optical Systems

Lecture 7: PSF and OTF
2019-05-27
Herbert Gross
<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Topic</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>08.04.</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
</tr>
<tr>
<td>2</td>
<td>15.04.</td>
<td>Materials and Components</td>
<td>Dispersion, anormal dispersion, glass map, liquids and plastics, lenses, mirrors, aspheres, diffractive elements</td>
</tr>
<tr>
<td>3</td>
<td>29.04.</td>
<td>Paraxial Optics</td>
<td>Paraxial approximation, basic notations, imaging equation, multi-component systems, matrix calculation, Lagrange invariant, phase space visualization</td>
</tr>
<tr>
<td>4</td>
<td>06.05.</td>
<td>Optical Systems</td>
<td>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
</tr>
<tr>
<td>5</td>
<td>13.05.</td>
<td>Geometrical Aberrations</td>
<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatical aberrations, Seidels surface contributions</td>
</tr>
<tr>
<td>6</td>
<td>20.05.</td>
<td>Wave Aberrations</td>
<td>Fermat principle and Eikonal, wave aberrations, expansion and higher orders, Zernike polynomials, measurement of system quality</td>
</tr>
<tr>
<td>7</td>
<td>27.05.</td>
<td>PSF and Transfer function</td>
<td>Diffraction, point spread function, PSF with aberrations, optical transfer function, Fourier imaging model</td>
</tr>
<tr>
<td>8</td>
<td>03.06.</td>
<td>Further Performance Criteria</td>
<td>Rayleigh and Marechal criteria, Strehl definition, 2-point resolution, MTF-based criteria, further options</td>
</tr>
<tr>
<td>9</td>
<td>17.06.</td>
<td>Optimization and Correction</td>
<td>Principles of optimization, initial setups, constraints, sensitivity, optimization of optical systems, global approaches</td>
</tr>
<tr>
<td>10</td>
<td>24.06.</td>
<td>Correction Principles I</td>
<td>Symmetry, lens bending, lens splitting, special options for spherical aberration, astigmatism, coma and distortion, aspheres</td>
</tr>
<tr>
<td>11</td>
<td>01.07.</td>
<td>Correction Principles II</td>
<td>Field flattening and Petzval theorem, chromatical correction, achromate, apochromate, sensitivity analysis, diffractive elements</td>
</tr>
<tr>
<td>12</td>
<td>08.07.</td>
<td>Optical System Classification</td>
<td>Overview, photographic lenses, microscopic objectives, lithographic systems, eyepieces, scan systems, telescopes, endoscopes</td>
</tr>
</tbody>
</table>
Contents

1. Ideal point spread function
2. PSF with aberrations
3. Strehl ratio
4. Two-point-resolution
5. Optical transfer function
6. Resolution and contrast
Huygens Principle

- Every point on a wave is the origin of a new spherical wave (green)
- The envelope of all Huygens wavelets forms the overall wave front (red)
- Light also enters the geometrical shadow region
- The vectorial superposition principle requires full coherence
Diffraction at the System Aperture

- Self luminous points: emission of spherical waves
- Optical system: only a limited solid angle is propagated, the truncation of the spherical wave results in a finite angle light cone
- In the image space: incomplete constructive interference of partial waves, the image point is spreaded
- The optical systems works as a low pass filter

\[ \Delta x = \frac{1.22 \lambda}{NA} \]
PSF by Huygens Principle

- Huygens wavelets correspond to vectorial field components:
  - represented by a small arrow
  - the phase is represented by the direction
  - the amplitude is represented by the length
- Zeros in the diffraction pattern: destructive interference
- Ideal point spread function:
- **Apodization:** variable lengths of arrows

- **Aberrations:** variable orientation of arrows
Fraunhofer Point Spread Function

- Rayleigh-Sommerfeld diffraction integral, Mathematical formulation of the Huygens-principle

\[ E_I(\vec{r}) = -\frac{i}{\lambda} \int \int E(\vec{r}') \cdot \frac{e^{i\vec{k}|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} \cos \theta d\theta' d\phi' \]

- Fraunhofer approximation in the far field for large Fresnel number

\[ N_F = \frac{r_p^2}{\lambda \cdot z} \approx 1 \]

- Optical systems: numerical aperture NA in image space
  Pupil amplitude/transmission/illumination \( T(x_p, y_p) \)
  Wave aberration \( W(x_p, y_p) \)
  Complex pupil function \( A(x_p, y_p) \)
  Transition from exit pupil to image plane

\[ E(x', y') = \int \int_{AP} T(x_p, y_p) \cdot e^{2\pi i W(x_p, y_p)} \cdot e^{\frac{2\pi i}{\lambda R_{AP}} (x_p x' + y_p y')} dx_p dy_p \]

- Point spread function (PSF): Fourier transform of the complex pupil function

\[ A(x_p, y_p) = T(x_p, y_p) \cdot e^{2\pi i W(x_p, y_p)} \]
Perfect Point Spread Function

Circular homogeneous illuminated aperture: intensity distribution

- **transversal: Airy scale**
  \[ D_{\text{Airy}} = \frac{1.22 \cdot \lambda}{NA} \]

- **axial: sinc scale**
  \[ R_E = \frac{n \cdot \lambda}{NA^2} \]

- Resolution transversal better than axial: \( \Delta x < \Delta z \)

Scaled coordinates according to Wolf:

- **axial**:
  \[ u = 2 \pi z n / \lambda NA^2 \]

- **transversal**:
  \[ v = 2 \pi x / \lambda NA \]

Ref: M. Kempe
Ideal Psf

\[ I(r,z) \]

- focal point
- spread spot
- axial sinc^2
- optical axis
- aperture cone
- image plane
- lateral Airy
Abbe Resolution and Assumptions

- Abbe resolution with scaling to $\lambda$/NA: Assumptions for this estimation and possible changes

- A resolution beyond the Abbe limit is only possible with violating of certain assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Resolution enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Circular pupil</td>
<td>ring pupil, dipol, quadrupole</td>
</tr>
<tr>
<td>2  Perfect correction</td>
<td>complex pupil masks</td>
</tr>
<tr>
<td>3  homogeneous illumination</td>
<td>dipol, quadrupole</td>
</tr>
<tr>
<td>4  Illumination incoherent</td>
<td>partial coherent illumination</td>
</tr>
<tr>
<td>5  no polarization</td>
<td>special radiale polarization</td>
</tr>
<tr>
<td>6  Scalar approximation</td>
<td></td>
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<tr>
<td>7  stationary in time</td>
<td>scanning, moving gratings</td>
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<tr>
<td>8  quasi monochromatic</td>
<td></td>
</tr>
<tr>
<td>9  circular symmetry</td>
<td>oblique illumination</td>
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<tr>
<td>10 far field conditions</td>
<td>near field conditions</td>
</tr>
<tr>
<td>11 linear emission/excitation</td>
<td>non linear methods</td>
</tr>
</tbody>
</table>
Perfect Lateral Point Spread Function: Airy

- Airy function:
  Perfect point spread function for several assumptions

- Distribution of intensity:

\[
I(r) = \left[2 \cdot J_1\left(\frac{2\pi r}{\lambda} NA\right)\right]^2
\]

- Normalized transverse coordinate

\[
x = \frac{2\pi ar}{\lambda R} = kr \sin \theta' = \frac{akr}{R} = ak \sin \theta'
\]

- Airy diameter: distance between the two zero points, diameter of first dark ring

\[
D_{Airy} = \frac{1.21976 \cdot \lambda}{n' \cdot \sin \theta'}
\]
Perfect Lateral Point Spread Function: Airy

Airy distribution:

- Gray scale picture
- Zeros non-equidistant
- Logarithmic scale
- Encircled energy
Perfect Axial Point Spread Function

- Axial distribution of intensity
  Corresponds to defocus

- Normalized axial coordinate
  \[ \bar{z} = \frac{\pi NA^2}{2 \cdot \lambda} \cdot \frac{z}{4} = \frac{u}{4} \]

- Scale for depth of focus: Rayleigh length
  \[ R_E = \frac{\lambda}{n' \sin^2 u'} = \frac{n' \lambda}{NA^2} \]

- Zero crossing points:
  equidistant and symmetric,
  Distance zeros around image plane \( 4R_E \)

\[
I(z) = I_0 \cdot \left(\frac{\sin(\bar{z})}{\bar{z}}\right)^2 = I_o \cdot \left(\frac{\sin u / 4}{u / 4}\right)^2
\]
Defocussed Perfect Psf

- Perfect point spread function with defocus
- Representation with constant energy: extreme large dynamic changes

<table>
<thead>
<tr>
<th>Δz = -2RE</th>
<th>Δz = -1RE</th>
<th>focus</th>
<th>Δz = +1RE</th>
<th>Δz = +2RE</th>
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<tbody>
<tr>
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<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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<table>
<thead>
<tr>
<th>normalized intensity</th>
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<td><img src="image6.png" alt="Image" /></td>
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</table>

<table>
<thead>
<tr>
<th>I_{max} = 5.1%</th>
<th>I_{max} = 9.8%</th>
<th>I_{max} = 42%</th>
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<tbody>
<tr>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
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<th>constant energy</th>
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<tbody>
<tr>
<td><img src="image14.png" alt="Image" /></td>
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</tbody>
</table>
Psf with Aberrations

- Psf for some low order Zernike coefficients
- The coefficients are changed between $c_j = 0...0.7 \lambda$
- The peak intensities are renormalized
Axial and Lateral Ideal Point Spread Function

- Comparison of both cross sections

Ref: R. Hambach
Annular Ring Pupil

- Generation of Bessel beams

Ref: R. Hambach

![Diagram](image)

- Pupil intensity
- Pupil phase
- Intensity $I(r)$ at focal point, $z=10$

Ref:
Spherical Aberration

- Axial asymmetrical distribution off axis
- Peak moves

Ref: R. Hambach
Gaussian Illumination

- Known profile of gaussian beams

Ref: R. Hambach
Strehl Ratio

- Important criterion for diffraction limited systems: Strehl ratio (Strehl definition)
  Ratio of real peak intensity (with aberrations) referenced on ideal peak intensity

\[
D_S = \frac{I_{\text{PSF}}^{(\text{real})}(0,0)}{I_{\text{PSF}}^{(\text{ideal})}(0,0)}
\]

- \( D_S \) takes values between 0...1
  \( D_S = 1 \) is perfect

- Critical in use: the complete information is reduced to only one number

- The criterion is useful for 'good' systems with values \( D_S > 0.5 \)
Approximations for the Strehl Ratio

- Approximation of Marechal:
  (useful for $D_s > 0.5$)
  but negative values possible

- Bi-quadratic approximation

- Exponential approach

- Computation of the Marechal approximation with the coefficients of Zernike

$$D_s = 1 - 4\pi^2 \left( \frac{W_{rms}}{\lambda} \right)^2$$

$$D_s = \left[ 1 - 2\pi^2 \cdot \left( \frac{W_{rms}}{\lambda} \right)^2 \right]^2$$

$$D_s = e^{-4\pi^2 \cdot \left( \frac{W_{rms}}{\lambda} \right)^2}$$

$$D_s = 1 - \left( \frac{2\pi}{\lambda} \right)^2 \cdot \left[ \sum_{n=1}^{N} \frac{c_{n0}^2}{n+1} + \frac{1}{2} \sum_{n=1}^{N} \sum_{m=0}^{n} \frac{c_{nm}^2}{n+1} \right]$$
In the case of defocus, the Rayleigh and the Marechal criterion delivers a Strehl ratio of

\[ D_s = \frac{8}{\pi^2} = 0.8106 \approx 0.8 \]

The criterion \( D_s > 80\% \) therefore also corresponds to a diffraction limit.

This value is generalized for all aberration types.

<table>
<thead>
<tr>
<th>aberration type</th>
<th>coefficient</th>
<th>Marechal approximated Strehl</th>
<th>exact Strehl</th>
</tr>
</thead>
<tbody>
<tr>
<td>defocus Seidel</td>
<td>( a_{20} = 0.25 )</td>
<td>0.7944</td>
<td>( \frac{8}{\pi^2} = 0.8106 )</td>
</tr>
<tr>
<td>defocus Zernike</td>
<td>( c_{20} = 0.125 )</td>
<td>0.7944</td>
<td>0.8106</td>
</tr>
<tr>
<td>spherical aberration Seidel</td>
<td>( a_{40} = 0.25 )</td>
<td>0.7807</td>
<td>0.8003</td>
</tr>
<tr>
<td>spherical aberration Zernike</td>
<td>( c_{40} = 0.167 )</td>
<td>0.7807</td>
<td>0.8003</td>
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<tr>
<td>astigmatism Seidel</td>
<td>( a_{22} = 0.25 )</td>
<td>0.8458</td>
<td>0.8572</td>
</tr>
<tr>
<td>astigmatism Zernike</td>
<td>( c_{22} = 0.125 )</td>
<td>0.8972</td>
<td>0.9021</td>
</tr>
<tr>
<td>coma Seidel</td>
<td>( a_{31} = 0.125 )</td>
<td>0.9229</td>
<td>0.9260</td>
</tr>
<tr>
<td>coma Zernike</td>
<td>( c_{31} = 0.125 )</td>
<td>0.9229</td>
<td>0.9260</td>
</tr>
</tbody>
</table>
Criteria for measuring the degradation of the point spread function:
1. Strehl ratio
2. width/threshold diameter
3. second moment of intensity distribution
4. area equivalent width
5. correlation with perfect PSF
6. power in the bucket
Transverse resolution of an image:
- Detection of object details / fine structures
- Basic formula of Abbe

Fundamental dependence of the resolution from:
1. Wavelength
2. Numerical aperture angle
3. Refractive index
4. Prefactor, depends on geometry, coherence, polarization, illumination, ...

Basic possibilities to increase resolution:
1. Shorter wavelength (DUV lithography)
2. Higher aperture angle (expensive, 75° in microscopy)
3. Higher index (immersion)
4. Special polarization, optimal partial coherence, ...

Assumptions for the validity of the formula:
1. No evanescent waves (no near field effects)
2. No non-linear effects (2-photon)
Rayleigh criterion for 2-point resolution
Maximum of psf coincides with zeros of neighbouring psf

- Contrast: $V = 0.15$

- Decrease of intensity between peaks $I = 0.735 I_0$

\[ \Delta x = \frac{1}{2} D_{\text{Airy}} = \frac{0.61 \cdot \lambda}{n \cdot \sin u} \]
Incoherent 2-Point-Resolution: Sparrow Criterion

- Criterion of Sparrow: vanishing derivative in the center between two point intensity distribution, corresponds to vanishing contrast

\[
\left( \frac{d^2 I(x)}{dx^2} \right)_{x=0} = 0
\]

- Modified formula

\[
\Delta x_{Sparrow} = \frac{0.474 \cdot \lambda}{n \cdot \sin \theta} = 0.385 \cdot D_{Airy} = 0.770 \cdot \Delta x_{Rayleigh}
\]

- Usually needs a priory information

- Applicable also for non-Airy distributions

- Used in astronomy
Incoherent 2-point Resolution Criterions

- Visual resolution limit:
  Good contrast visibility $V = 26\%$:

- Total resolution:
  Coincidence of neighbouring zero points of the Airy distributions: $V = 1$
  Extremly conservative criterion

- Contrast limit: $V = 0$:
  Intensity $I = 1$ between peaks

\[
\Delta x = \frac{0.83 \cdot \lambda}{n \cdot \sin u} = 0.680 \cdot D_{\text{Airy}}
\]

\[
\Delta x = D_{\text{Airy}} = \frac{1.22 \cdot \lambda}{n \cdot \sin u}
\]

\[
\Delta x = \frac{0.51 \cdot \lambda}{n \cdot \sin u} = 0.418 \cdot D_{\text{Airy}}
\]
2-Point Resolution

- Distance of two neighboring object points
- Distance $\Delta x$ scales with $\lambda / \sin \theta$
- Different resolution criteria for visibility / contrast $V$

\[ \Delta x = 1.22 \frac{\lambda}{\sin \theta} \quad \text{total} \]
\[ \Delta x = 0.68 \frac{\lambda}{\sin \theta} \quad \text{visual} \]
\[ \Delta x = 0.61 \frac{\lambda}{\sin \theta} \quad \text{Rayleigh} \]
\[ \Delta x = 0.474 \frac{\lambda}{\sin \theta} \quad \text{Sparrow} \]
2-Point Resolution

- Intensity distributions below 10% for 2 points with different $\Delta x$ (scaled on Airy)

$\Delta x = 2.0$  $\Delta x = 1.22$  $\Delta x = 1.0$  $\Delta x = 0.83$

$\Delta x = 0.61$  $\Delta x = 0.474$  $\Delta x = 0.388$  $\Delta x = 0.25$
Microscopical resolution as a function of the numerical aperture
Grating Diffraction and Resolution

- Arbitrary object expanded into a spatial frequency spectrum by Fourier transform
- Every frequency component is considered separately
- To resolve a spatial detail, at least two orders must be supported by the system

\[ g \cdot \sin \theta = m \cdot \lambda \]
\[ g = \frac{\lambda}{\sin \theta} = \frac{\lambda}{NA} \]
\[ g = \frac{\lambda}{2 \cdot NA} \]

Ref: M. Kempe

Ref: M. Kempe
A structure of the object is resolved, if the first diffraction order is propagated through the optical imaging system.

The fidelity of the image increases with the number of propagated diffracted orders.
Resolution of Fourier Components

- Object point
- Object detail
- Sum

Decomposition of Fourier components (sin waves)

- Image for low NA
- Image for high NA
- Object

High spatial frequencies
Numerical aperture resolved frequencies
Low spatial frequencies

Ref: D. Aronstein / J. Bentley
Optical Transfer Function: Definition

- Normalized optical transfer function (OTF) in frequency space:
  Fourier transform of the Psf-intensity

- Absolute value of OTF: modulation transfer function MTF
  Gives the contrast at a special spatial frequency of a sine grating

- OTF: Autocorrelation of shifted pupil function, Duffieux-integral
  Interpretation: interference of 0th and 1st diffraction of the light in the pupil

\[ H_{OTF}(v_x, v_y) = \hat{F}[I_{PSF}(x, y)] \]

\[
H_{OTF}(v_x) = \frac{\int_{-\infty}^{\infty} P(x_p + \frac{\lambda f v_x}{2}) \cdot P^*(x_p - \frac{\lambda f v_x}{2}) dx_p}{\int_{-\infty}^{\infty} |P(x_p)|^2 dx_p}
\]
Interpretation of the Duffieux integral:

- Interpretation of the Duffieux integral: overlap area of 0th and 1st diffraction order, interference between the two orders
- The area of the overlap corresponds to the information transfer of the structural details
- Frequency limit of resolution: areas completely separated
Duffieux Integral and Contrast

- Separation of pupils for 0. and +/-1. Order

- MTF function

- Image contrast for sin-object

Ref: W. Singer
Optical Transfer Function of a Perfect System

- Aberration free circular pupil:
  Reference frequency
  \[ v_o = \frac{a}{\lambda f} = \frac{\sin u'}{\lambda} \]

- Cut-off frequency:
  \[ v_G = 2v_0 = \frac{2na}{\lambda f} = \frac{2n \sin u'}{\lambda} \]

- Analytical representation
  \[ H_{MTF}(v) = \frac{2}{\pi} \left[ \arccos \left( \frac{v}{2v_0} \right) - \left( \frac{v}{2v_0} \right) \sqrt{1 - \left( \frac{v}{2v_0} \right)^2} \right] \]

- Separation of the complex OTF function into:
  - absolute value: modulation transfer MTF
  - phase value: phase transfer function PTF

\[ H_{OTF}(v_x, v_y) = H_{MTF}(v_x, v_y) \cdot e^{iH_{PTF}(v_x, v_y)} \]
Contrast / Visibility

- The MTF-value corresponds to the intensity contrast of an imaged sin grating
- Visibility

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

- The maximum value of the intensity is not identical to the contrast value since the minimal value is finite too
- Concrete values:

<table>
<thead>
<tr>
<th>$\Delta I$</th>
<th>$I_{\text{max}}$</th>
<th>$V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010</td>
<td>0.990</td>
<td>0.980</td>
</tr>
<tr>
<td>0.020</td>
<td>0.980</td>
<td>0.961</td>
</tr>
<tr>
<td>0.050</td>
<td>0.950</td>
<td>0.905</td>
</tr>
<tr>
<td>0.100</td>
<td>0.900</td>
<td>0.818</td>
</tr>
<tr>
<td>0.111</td>
<td>0.899</td>
<td>0.800</td>
</tr>
<tr>
<td>0.150</td>
<td>0.850</td>
<td>0.739</td>
</tr>
<tr>
<td>0.200</td>
<td>0.800</td>
<td>0.667</td>
</tr>
<tr>
<td>0.300</td>
<td>0.700</td>
<td>0.538</td>
</tr>
</tbody>
</table>
Convolution of the object intensity distribution $I(x)$ changes:
1. Peaks are reduced
2. Minima are raised
3. Steep slopes are declined
4. Contrast is decreased
Due to the asymmetric geometry of the psf for finite field sizes, the MTF depends on the azimuthal orientation of the object structure.

Generally, two MTF curves are considered for sagittal/tangential oriented object structures.
Real MTF of system with residual aberrations:
1. contrast decreases with defocus
2. higher spatial frequencies have stronger decrease

Zernike coefficients:
- $c_5 = 0.02$
- $c_7 = 0.025$
- $c_8 = 0.03$
- $c_9 = 0.05$
• Resolution/contrast criterion:
  Ratio of contrasts with/without aberrations for one selected spatial frequency

\[ \Delta g_{MTF}(v) = \frac{g_{MTF}^{(real)}(v)}{g_{MTF}^{(ideal)}(v)} \]

• Real systems:
  Choice of several application relevant frequencies
  e.g. photographic lens:
  10 Lp/mm, 20 Lp/mm, 40 Lp/mm
Modulation Transfer Function

- Photographic lenses with different performance

<table>
<thead>
<tr>
<th>Image height</th>
<th>Lens 1</th>
<th>f/3.5</th>
<th>Lens 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 c/mm</td>
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<td>40 c/mm</td>
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<td><img src="Image2.png" alt="Graph2" /></td>
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Calculation of MTF – Some more examples

1-dim case

circular pupil

Ring pupil = central obscuration (75%)

Apodization = reduced transmission at pupil edge (Gauss to 50%)

The transfer of frequencies depends on transmission of pupil
- Ring pupil → higher contrast near the diffraction limit
- Apodisation → increase of contrast at lower frequencies

Ref: B. Böhme
Resolution Test Chart: Siemens Star

- **a.** original
- **b.** good system
- **c.** defocus
- **d.** spherical
- **e.** astigmatism
- **f.** coma
Contrast and Resolution

- Contrast vs contrast as a function of spatial frequency
- Typical: contrast reduced for increasing frequency
- Compromise between resolution and visibility is not trivial and depends on application
Optical Transfer Function of a Perfect System

- Loss of contrast for higher spatial frequencies
Contrast / Resolution of Real Images

- Degradation due to
  1. loss of contrast
  2. loss of resolution