Design and Correction of Optical Systems

Lecture 7: Psf and Transfer Function

2013-05-29

Herbert Gross
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<thead>
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<th>Topic</th>
<th>Notes</th>
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<tr>
<td>1</td>
<td>10.04</td>
<td>Basics</td>
<td>Law of refraction, Fresnel formulas, optical system model, raytrace, calculation approaches</td>
</tr>
<tr>
<td>2</td>
<td>17.04</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>24.04</td>
<td>Paraxial Optics</td>
<td>Paraxial approximation, basic notations, imaging equation, multi-component systems, matrix calculation, Lagrange invariant, phase space visualization</td>
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<td>4</td>
<td>08.05</td>
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<td>Pupil, ray sets and sampling, aperture and vignetting, telecentricity, symmetry, photometry</td>
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<td>5</td>
<td>15.05</td>
<td>Geometrical Aberrations</td>
<td>Longitudinal and transverse aberrations, spot diagram, polynomial expansion, primary aberrations, chromatical aberrations, Seidels surface contributions</td>
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<td>6</td>
<td>22.05</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>29.05</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>05.06</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>12.06</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>19.06</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>26.06</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>03.07</td>
<td>Optical System Classification</td>
<td>Overview, photographic lenses, microscopic objectives, lithographic systems, eyepieces, scan systems, telescopes, endoscopes</td>
</tr>
<tr>
<td>13</td>
<td>10.07</td>
<td>Special System Examples</td>
<td>Zoom systems, confocal systems</td>
</tr>
</tbody>
</table>
1. Ideal point spread function
2. PSF with aberrations
3. Strehl ration
4. Two-point-resolution
5. Optical transfer function
6. Resolution and contrast
- 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: uncomplete constructive interference of partial waves, the image point is spreaded
- The optical systems works as a low pass filter
- Huygens wavelets correspond to vectorial field components
- The phase is represented by the direction
- The amplitude is represented by the length
- Zeros in the diffraction pattern: destructive interference
- Aberrations from spherical wave: reduced constructive superposition
Fraunhofer Point Spread Function

- Rayleigh-Sommerfeld diffraction integral, Mathematical formulation of the Huygens-principle
  \[ E_I(\vec{r}) = -\frac{i}{\lambda} \iint E(\vec{r}') \frac{e^{ik|\vec{r}-\vec{r}'|}}{|\vec{r} - \vec{r}'|} \cos \theta d\theta dx' dy' \]

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

- Point spread function (PSF): Fourier transform of the complex pupil function
  \[ A(x_p, y_p) = T(x_p, y_p) \cdot e^{2\pi i W(x_p, y_p)} \]
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: \( u = 2 \pi \frac{z \cdot n}{\lambda \cdot NA^2} \)
- transversal: \( v = 2 \pi \frac{x}{\lambda \cdot NA} \)

Ref: M. Kempe
Ideal Psf

- $I(r,z)$
- focal point
- spread spot
- axial
- sinc²
- optical axis
- aperture cone
- lateral Airy
- image plane
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</td>
<td>Circular pupil, ring pupil, dipol, quadrupole</td>
</tr>
<tr>
<td>2</td>
<td>Perfect correction, complex pupil masks</td>
</tr>
<tr>
<td>3</td>
<td>homogeneous illumination, dipol, quadrupole</td>
</tr>
<tr>
<td>4</td>
<td>Illumination incoherent, partial coherent illumination</td>
</tr>
<tr>
<td>5</td>
<td>no polarization, special radiale polarization</td>
</tr>
<tr>
<td>6</td>
<td>Scalar approximation</td>
</tr>
<tr>
<td>7</td>
<td>stationary in time, scanning, moving gratings</td>
</tr>
<tr>
<td>8</td>
<td>quasi monochromatic</td>
</tr>
<tr>
<td>9</td>
<td>circular symmetry, oblique illumination</td>
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<tr>
<td>10</td>
<td>far field conditions, near field conditions</td>
</tr>
<tr>
<td>11</td>
<td>linear emission/excitation, 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:
  \[ I(r) = \left( \frac{2 \cdot J_1 \left( \frac{2\pi r}{\lambda} \right)}{\frac{2\pi r}{\lambda} \cdot NA} \right)^2 \]

- Normalized transverse coordinate
  \[ x = \frac{2\pi ar}{\lambda R} = kr \sin u' = \frac{akr}{R} = ak \sin \theta' \]

- Airy diameter: distance between the two zero points, diameter of first dark ring
  \[ D_{Airy} = \frac{1.21976 \cdot \lambda}{n' \cdot \sin u'} \]
Perfect Lateral Point Spread Function: Airy

Airy distribution:

- Gray scale picture
- Zeros non-equidistant
- Logarithmic scale
- Encircled energy
Axial distribution of intensity
Corresponds to defocus

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

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

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

\[ I(z) = I_0 \cdot \left( \frac{\sin(z)}{z} \right)^2 = I_o \cdot \left( \frac{\sin u / 4}{u / 4} \right)^2 \]
- Perfect point spread function with defocus
- Representation with constant energy: extreme large dynamic changes

<table>
<thead>
<tr>
<th>Δz = -2R_E</th>
<th>Δz = -1R_E</th>
<th>focus</th>
<th>Δz = +1R_E</th>
<th>Δz = +2R_E</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td><em>(I_{max} = 5.1%)</em></td>
<td><em>(I_{max} = 9.8%)</em></td>
<td><em>(I_{max} = 42%)</em></td>
<td><em>(I_{max} = 9.8%)</em></td>
<td><em>(I_{max} = 5.1%)</em></td>
</tr>
</tbody>
</table>

Normalized intensity
Constant energy
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
**Strehl Ratio**

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

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

- \(D_S\) 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

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

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

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

$$D_s = 1 - \left(\frac{2\pi}{\lambda}\right)^2 \cdot \left[\sum_{n=1}^{N} \frac{c_{n0}^2}{n+1} + \frac{1}{2} \sum_{n=1}^{N} \sum_{m=0}^{n} \frac{c_{nm}^2}{n+1}\right]$$
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>
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<tbody>
<tr>
<td>defocus</td>
<td>Seidel</td>
<td>( a_{20} = 0.25 )</td>
<td>0.7944</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \frac{8}{\pi^2} = 0.8106 )</td>
</tr>
<tr>
<td>defocus</td>
<td>Zernike</td>
<td>( c_{20} = 0.125 )</td>
<td>0.7944</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8106</td>
</tr>
<tr>
<td>spherical aberration</td>
<td>Seidel</td>
<td>( a_{40} = 0.25 )</td>
<td>0.7807</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8003</td>
</tr>
<tr>
<td>spherical aberration</td>
<td>Zernike</td>
<td>( c_{40} = 0.167 )</td>
<td>0.7807</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.8003</td>
</tr>
<tr>
<td>astigmatism</td>
<td>Seidel</td>
<td>( a_{22} = 0.25 )</td>
<td>0.8458</td>
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<td></td>
<td>0.8572</td>
</tr>
<tr>
<td>astigmatism</td>
<td>Zernike</td>
<td>( c_{22} = 0.125 )</td>
<td>0.8972</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.9021</td>
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<tr>
<td>coma</td>
<td>Seidel</td>
<td>( a_{31} = 0.125 )</td>
<td>0.9229</td>
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<td></td>
<td>0.9260</td>
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<tr>
<td>coma</td>
<td>Zernike</td>
<td>( c_{31} = 0.125 )</td>
<td>0.9229</td>
</tr>
<tr>
<td></td>
<td></td>
<td></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

- **Modified formula**
  \[
  \Delta x_{Sparrow} = \frac{0.474 \cdot \lambda}{n \cdot \sin u} = 0.385 \cdot D_{Airy} \\
  = 0.770 \cdot \Delta x_{Rayleigh}
  \]

- **Usually needs a priory information**

- **Applicable also for non-Airy distributions**

- **Used in astronomy**

\[
\left( \frac{d^2 I(x)}{dx^2} \right)_{x=0} = 0
\]
Incoherent 2-point Resolution Criteria

- 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 $V$

\[ \Delta x = 1.22 \frac{\lambda}{\sin \theta} \]

**Total**

\[ V = 1 \]

\[ \Delta x = 0.68 \frac{\lambda}{\sin \theta} \]

**Visual**

\[ V = 0.26 \]

\[ \Delta x = 0.61 \frac{\lambda}{\sin \theta} \]

**Rayleigh**

\[ V = 0.15 \]

\[ \Delta x = 0.474 \frac{\lambda}{\sin \theta} \]

**Sparrow**

\[ V = 0 \]
2-Point Resolution

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

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

$\Delta x = 0.61$  
$\Delta x = 0.474$  
$\Delta x = 0.388$  
$\Delta x = 0.25$
Incoherent Resolution: Dependence on NA

- Microscopical resolution as a function of the numerical aperture

NA = 0.2
NA = 0.3
NA = 0.45
NA = 0.9
- Large aberrations:
  Waveoptical calculation shows bad conditioning
- Wave aberrations small: diffraction limited, geometrical spot too small and wrong
- Approximation for the intermediate range:

\[ D_{\text{Spot}} = \sqrt{D_{\text{Airy}}^2 + D_{\text{Geo}}^2} \]
Optical Transfer Function: Definition

- Normalized optical transfer function (OTF) in frequency space

\[
H_{OTF}(v_x, v_y) = \frac{\int \int |g(x_p, y_p)|^2 \cdot e^{-2\pi i (x_p v_x + y_p v_y)} dx_p dy_p}{\int \int |g(x_p, y_p)|^2 dx_p dy_p}
\]

- Fourier transform of the Psf-intensity

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

- OTF: Autocorrelation of shifted pupil function, Duffieux-integral

\[
H_{OTF}(v_x, v_y) = \frac{\int \int P(x_p + \frac{\lambda f v_x}{2}, y_p + \frac{\lambda f v_y}{2}) \cdot P^*(x_p - \frac{\lambda f v_x}{2}, y_p - \frac{\lambda f v_y}{2}) dx_p dy_p}{\int \int |P(x_p, y_p)|^2 dx_p dy_p}
\]

- Absolute value of OTF: modulation transfer function (MTF)

- MTF is numerically identical to contrast of the image of a sine grating at the corresponding spatial frequency
MTF and Contrast

- **Object**

\[
I_{obj}(x) = c + a \cdot \cos(2\pi v_0 x)
\]

- **Contrast**

\[
V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{(c + a) - (c - a)}{(c + a) + (c - a)} = \frac{a}{c}
\]

- **Object spectrum**

\[
\bar{I}_{obj}(v) = \hat{F}[I_{obj}(x)] = c \cdot \delta(v - 0) + \frac{a}{2} \cdot \delta(v - v_0) + \frac{a}{2} \cdot \delta(v + v_0)
\]

- **Image spectrum**

\[
\bar{I}_{ima}(v) = \bar{I}_{obj}(v) \cdot H_{MTF}(v)
\]

- **Image**

\[
I_{ima}(x') = \hat{F}^{-1}\left[\bar{I}_{ima}(v)\right] = \hat{F}^{-1}\left[\bar{I}_{obj}(v) \cdot H_{MTF}(v)\right]
\]

\[
= \hat{F}^{-1}\left[c \cdot H_{MTF}(v) \cdot \delta(v - 0) + \frac{a}{2} \cdot H_{MTF}(v) \cdot \delta(v - v_0) + \frac{a}{2} \cdot H_{MTF}(v) \cdot \delta(v + v_0)\right]
\]

\[
= c \cdot H_{MTF}(0) + \frac{a}{2} \cdot H_{MTF}(v_0) \cdot e^{2\pi i v_0 x} + \frac{a}{2} \cdot H_{MTF}(-v_0) \cdot e^{-2\pi i v_0 x}
\]

\[
= c + a \cdot H_{MTF}(v_0) \cdot \cos(2\pi v_0 x)
\]
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
Resolution of Fourier Components

- Object detail
- High spatial frequencies
- Low spatial frequencies
- Numerical aperture

Decomposition of Fourier components (sin waves):
- Object
- Image for low NA
- Image for high NA
- Object

Ref: D. Aronstein / J. Bentley
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
  \[ v_0 = \frac{a}{\lambda f} = \frac{\sin u'}{\lambda} \]

- 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>0.889</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>
- 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 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
Contrast / Resolution of Real Images

- Degradation due to
  1. loss of contrast
  2. loss of resolution
Summary of Important Topics

- Point spread function: edge diffraction interference effect
- Perfect transverse Psf and Airy distribution
- Perfect axial Psf and depth of focus
- PSF with aberrations: broadening, special symmetries
- 2-point resolution, Rayleigh criterion
- Optical transfer function: FFT of Psf intensity
- Test charts for qualitative and fast evaluations
- Optimization contrast vs resolution: not trivial, depends on application