<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Topic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.10.</td>
<td>Paraxial imaging</td>
<td>paraxial optics, fundamental laws of geometrical imaging, compound systems</td>
</tr>
<tr>
<td>2</td>
<td>06.11.</td>
<td>Pupils, Fourier optics, Hamiltonian coordinates</td>
<td>pupil definition, basic Fourier relationship, phase space, analogy optics and mechanics, Hamiltonian coordinates</td>
</tr>
<tr>
<td>3</td>
<td>13.11.</td>
<td>Eikonal</td>
<td>Fermat principle, stationary phase, Eikonals, relation rays-waves, geometrical approximation, inhomogeneous media</td>
</tr>
<tr>
<td>4</td>
<td>20.11.</td>
<td>Aberration expansions</td>
<td>single surface, general Taylor expansion, representations, various orders, stop shift formulas</td>
</tr>
<tr>
<td>5</td>
<td>27.11.</td>
<td>Representation of aberrations</td>
<td>different types of representations, fields of application, limitations and pitfalls, measurement of aberrations</td>
</tr>
<tr>
<td>6</td>
<td>04.12.</td>
<td>Spherical aberration</td>
<td>phenomenology, sph-free surfaces, skew spherical, correction of sph, aspherical surfaces, higher orders</td>
</tr>
<tr>
<td>7</td>
<td>11.12.</td>
<td>Distortion and coma</td>
<td>phenomenology, relation to sine condition, aplanatic systems, effect of stop position, various topics, correction options</td>
</tr>
<tr>
<td>8</td>
<td>18.12.</td>
<td>Astigmatism and curvature</td>
<td>phenomenology, Coddington equations, Petzval law, correction options</td>
</tr>
<tr>
<td>9</td>
<td>08.01.</td>
<td>Chromatical aberrations</td>
<td>Dispersion, axial chromatical aberration, transverse chromatical aberration, spherochromatism, secondary spocerum</td>
</tr>
<tr>
<td>10</td>
<td>15.01.</td>
<td>Sine condition, aplanatism and isoplanatism</td>
<td>Sine condition, isoplanatism, relation to coma and shift invariance, pupil aberrations, Herschel condition, relation to Fourier optics</td>
</tr>
<tr>
<td>11</td>
<td>22.01.</td>
<td>Wave aberrations</td>
<td>definition, various expansion forms, propagation of wave aberrations</td>
</tr>
<tr>
<td>12</td>
<td>29.01.</td>
<td>Zernike polynomials</td>
<td>special expansion for circular symmetry, problems, calculation, optimal balancing, influence of normalization, measurement</td>
</tr>
<tr>
<td>13</td>
<td>05.02.</td>
<td>PSF and transfer function</td>
<td>ideal psf, psf with aberrations, Strehl ratio, transfer function, resolution and contrast</td>
</tr>
<tr>
<td>14</td>
<td>12.02.</td>
<td>Additional topics</td>
<td>Vectorial aberrations, generalized surface contributions, Aldis theorem, intrinsic and induced aberrations, revertability</td>
</tr>
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</table>
Contents

1. Ideal point spread function
2. PSF with aberrations
3. Strehl ratio
4. High NA vectorial PSF
5. Two-point-resolution
6. Optical transfer function
7. Resolution and contrast
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: uncomplete constructive interference of partial waves, the image point is spreaded
- The optical systems works as a low pass filter
PSF by Huygens Principle

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

Fraunhofer approximation in the far field for large Fresnel number

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

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

$$E_l(\bar{r}) = -\frac{i}{\lambda} \iint E(\bar{r}') \cdot \frac{e^{i\bar{k}|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|} \cdot \cos \theta \, dx' \, dy'$$

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

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

$$A(x_p, y_p) = T(x_p, y_p) \cdot e^{2\pi i W(x_p, y_p)}$$
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
- lateral Airy
- image plane

\[ r \]
\[ z \]
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>
</tr>
<tr>
<td>7  stationary in time</td>
<td>scanning, moving gratings</td>
</tr>
<tr>
<td>8  quasi monochromatic</td>
<td></td>
</tr>
<tr>
<td>9  circular symmetry</td>
<td>oblique illumination</td>
</tr>
<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**:
  \[ I(r) = \frac{2 \cdot J_1 \left( \frac{2\pi r}{\lambda} NA \right)}{2\pi r \cdot NA} \]
- **Normalized transverse coordinate**
  \[ x = \frac{2\pi ar}{\lambda R} = kr \sin u' = \frac{ak r}{R} = ak \sin \theta' \]
- **Airy diameter**: distance between the two zero points, diameter of first dark ring.

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

Airy distribution:

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

- Axial distribution of intensity
  Corresponds to defocus

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

- 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

<table>
<thead>
<tr>
<th>$\Delta z$</th>
<th>normalized intensity</th>
<th>constant energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-2R_E$</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>$-1R_E$</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>focus</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>$+1R_E$</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>$+2R_E$</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
</tr>
</tbody>
</table>

- $I_{\text{max}} = 5.1\%$
- $I_{\text{max}} = 9.8\%$
- $I_{\text{max}} = 42\%$
Psf with Aberrations

- Psf for some low order Zernike coefficients
- The coefficients are changed between $c_j = 0 \ldots 0.7 \lambda$
- 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

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

\[ D_S = \frac{\iiint A(x, y)e^{2\pi i W(x, y)} dxdy}{\iint A(x, y) dxdy} \]

- \( D_S \) 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>
</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>
</tr>
<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
High-NA Focusing

- Transfer from entrance to exit pupil in high-NA:
  1. Geometrical effect due to projection (photometry): apodization

  \[ A = A_0 \cdot \frac{1}{\sqrt[4]{1 - s^2 r^2}} \]

  with

  \[ s = \sin u = \frac{NA}{n} \]

- Tilt of field vector components

  \[ A = \frac{A_0}{2} \cdot \left[ 1 + \sqrt{1 - s^2 r^2} \right] \cdot \cos 2\theta \]
High-NA Focusing

- Total apodization corresponds to astigmatism
- Example calculations

\[ A_{x\text{-}lin}(r, \theta) = A_0(r, \theta) \cdot \frac{1 + \sqrt{1 - s^2 r^2} - \left(1 - \sqrt{1 - s^2 r^2}\right) \cdot \cos 2\theta}{2 \cdot \frac{4}{\sqrt{1 - s^2 r^2}}} \]
Vectorial representation of the diffraction integral according to Richards/Wolf

\[
\vec{E}(r', z') = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \vec{E}_0 \cdot e^{\frac{iu}{4\sin^2 \theta_0/2}} \begin{pmatrix} -i \cdot (I_0 + I_2 \cdot \cos 2\varphi) \\ -i \cdot I_2 \cdot \sin 2\varphi \\ -2 \cdot I_1 \cdot \cos \varphi \end{pmatrix}
\]

- Auxiliary integrals

\[
I_0(r', z') = \int_0^{\theta_o} \sqrt{\cos \theta} \cdot \sin \theta \cdot (1 + \cos \theta) \cdot J_0(kr' \sin \theta) \cdot e^{ikz' \cos \theta} \, d\theta
\]

\[
I_1(r', z') = \int_0^{\theta_o} \sqrt{\cos \theta} \cdot \sin^2 \theta \cdot J_1(kr' \sin \theta) \cdot e^{ikz' \cos \theta} \, d\theta
\]

\[
I_2(r', z') = \int_0^{\theta_o} \sqrt{\cos \theta} \cdot \sin \theta \cdot (1 - \cos \theta) \cdot J_2(kr' \sin \theta) \cdot e^{ikz' \cos \theta} \, d\theta
\]

- General: axial and cross components of polarization
Vectorial Diffraction at high NA

Linear Polarization

Pupil

\[ \text{NA} \]
High NA and Vectorial Diffraction

- Relative size of vectorial effects as a function of the numerical aperture
- Characteristic size of errors:

<table>
<thead>
<tr>
<th>error</th>
<th>axial</th>
<th>lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.52</td>
<td>0.98</td>
</tr>
<tr>
<td>0.001</td>
<td>0.18</td>
<td>0.68</td>
</tr>
</tbody>
</table>
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)

\[ \Delta x = k \cdot \frac{\lambda}{n \cdot \sin \theta} \]
Rayleigh criterion for 2-point resolution
Maximum of psf coincides with zeros of neighbouring psf

\[ \Delta x = \frac{1}{2} D_{Airy} = \frac{0.61 \cdot \lambda}{n \cdot \sin u} \]

- Contrast: \( V = 0.15 \)

- Decrease of intensity between peaks
  \( I = 0.735 I_0 \)
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

\[ \Delta x_{Sparrow} = \frac{0.474 \cdot \lambda}{n \cdot \sin u} \approx 0.385 \cdot D_{Airy} \]

\[ = 0.770 \cdot \Delta x_{Rayleigh} \]

- 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 $V = 26\%$:

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

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

  Extremely conservative criterion

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

$$\Delta x = \frac{1.22 \cdot \lambda}{n \cdot \sin u}$$

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

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

\[
\Delta x = 1.22 \frac{\lambda}{\sin \theta}
\]
\[
\text{total } V = 1
\]
\[
\Delta x = 0.68 \frac{\lambda}{\sin \theta}
\]
\[
\text{visual } V = 0.26
\]
\[
\Delta x = 0.61 \frac{\lambda}{\sin \theta}
\]
\[
\text{Rayleigh } V = 0.15
\]
\[
\Delta x = 0.474 \frac{\lambda}{\sin \theta}
\]
\[
\text{Sparrow } V = 0
\]
2-Point Resolution

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

- Microscopical resolution as a function of the numerical aperture
- Large aberrations:
  Waveoptical calculation shows bad conditioning
- Wave aberrations small: diffraction limited, geometrical spot too small and wrong
- Approximation for the intermediate range:

\[ D_{\text{Spot}} = \sqrt{D_{\text{Airy}}^2 + D_{\text{Geo}}^2} \]
Resolution of Fourier Components

Ref: D.Aronstein / J. Bentley
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**
  \[ V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{(c + a) - (c - a)}{(c + a) + (c - a)} = \frac{a}{c} \]

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

- **Image spectrum**
  \[ \tilde{I}_{ima}(v) = \tilde{I}_{obj}(v) \cdot H_{MTF}(v) \]

- **Image**
  \[ I_{ima}(x') = \hat{F}^{-1}[\tilde{I}_{ima}(v)] = \hat{F}^{-1}[\tilde{I}_{obj}(v) \cdot H_{MTF}(v)] \]
  \[ = \hat{F}^{-1} \left[ c \cdot H_{MTF}(v) \cdot \delta(v - 0) + \frac{a}{2} \cdot H_{MTF}(v) \cdot \delta(v - v_0) + \frac{a}{2} \cdot H_{MTF}(v) \cdot \delta(v + v_0) \right] \]
  \[ = c \cdot H_{MTF}(0) + \frac{a}{2} \cdot H_{MTF}(v_0) \cdot e^{2\pi i v_0 x} + \frac{a}{2} \cdot H_{MTF}(-v_0) \cdot e^{-2\pi i v_0 x} \]
  \[ = c + a \cdot H_{MTF}(v_0) \cdot \cos(2\pi v_0 x) \]
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
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>ΔI</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
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