MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 9

25.11.2024

Ye Pu
Sciences et techniques de l'ingénieur
École Polytechnique Fédérale de Lausanne
CH-1015 Lausanne

Outline

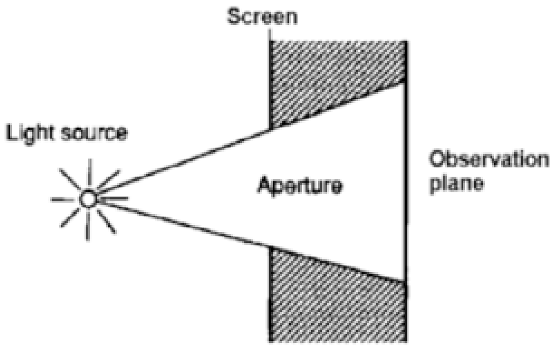
Theory

- Review of physical optics
- Physical optics modeling
  - Gaussian optics
  - Diffraction
- Imaging
  - Modulation transfer function
  - Point spread function

ZEMAX Practice

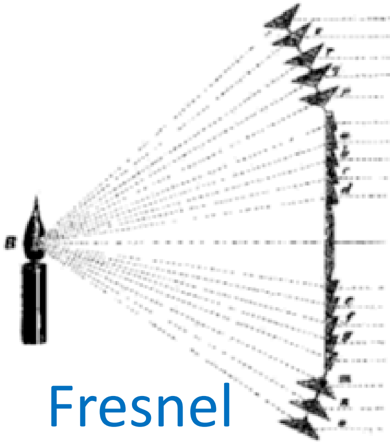
- ZEMAX physical optics modeling
  - MTF
  - PSF
  - Imaging simulation

Historical Development of the Theory of Light

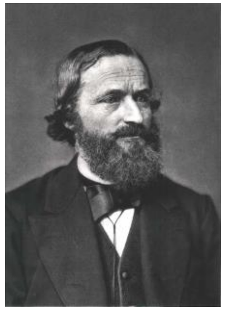


Grimaldi

Newton



Fresnel

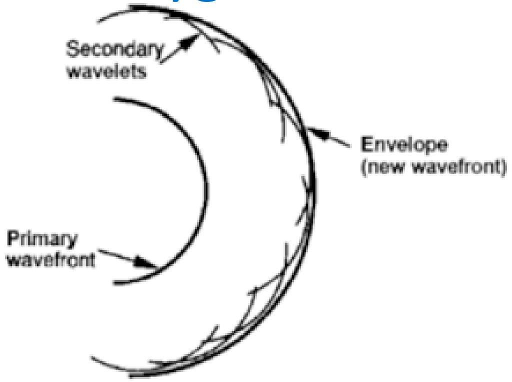


Sommerfeld

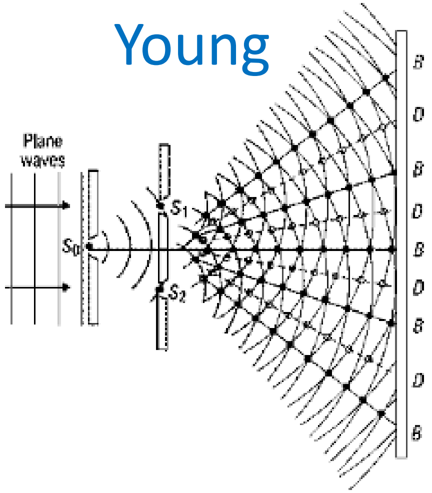
Kirchhoff

1665 1678 1704 1801 1818 1860 1882-96

Huygens



Young



Maxwell

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

Electromagnetics: From Vector to Scalar

Free-space Maxwell equation

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \varepsilon \mathbf{E} = 0$$

$$\nabla \cdot \mu \mathbf{H} = 0$$

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla \left(\cancel{\nabla \cdot \mathbf{E}}\right) - \nabla^2 \mathbf{E} = -\mu \frac{\partial}{\partial t} \nabla \times \mathbf{H}$$

$$\nabla \times (\nabla \times \mathbf{H}) = \nabla \left(\cancel{\nabla \cdot \mathbf{H}}\right) - \nabla^2 \mathbf{H} = \varepsilon \frac{\partial}{\partial t} \nabla \times \mathbf{E}$$

Scalar wave equation at point P and time t

$$\nabla^2 u(P,t) = \frac{n^2}{c^2} \frac{\partial^2 u(P,t)}{\partial t^2}$$

where u represents any component in $\mathbf{E}$ or $\mathbf{H}$

$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \qquad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

Separable variable

$$u(P,t) = A(P)T(t)$$

$$\frac{\nabla^2 A(P)}{A(P)} = -k^2$$

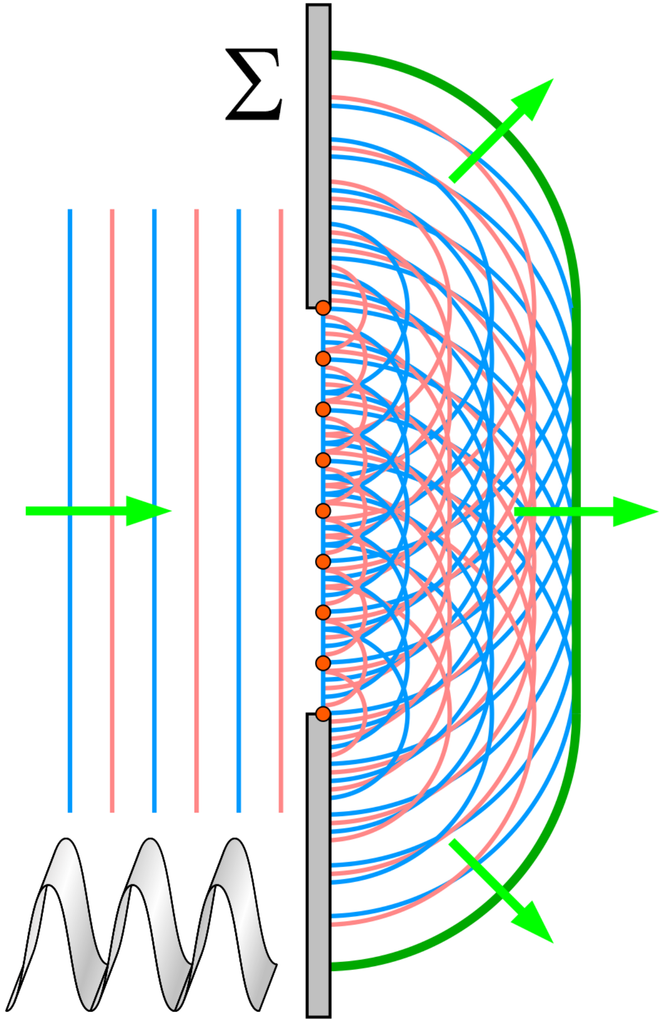
$$\frac{1}{c^2 T} \frac{d^2 T}{dt^2} = -k^2$$

Helmholtz Equation

$$\left(\nabla^2 + k^2\right) A(P) = 0$$

$$k = \frac{n\omega}{c} = \frac{2\pi}{\lambda}$$

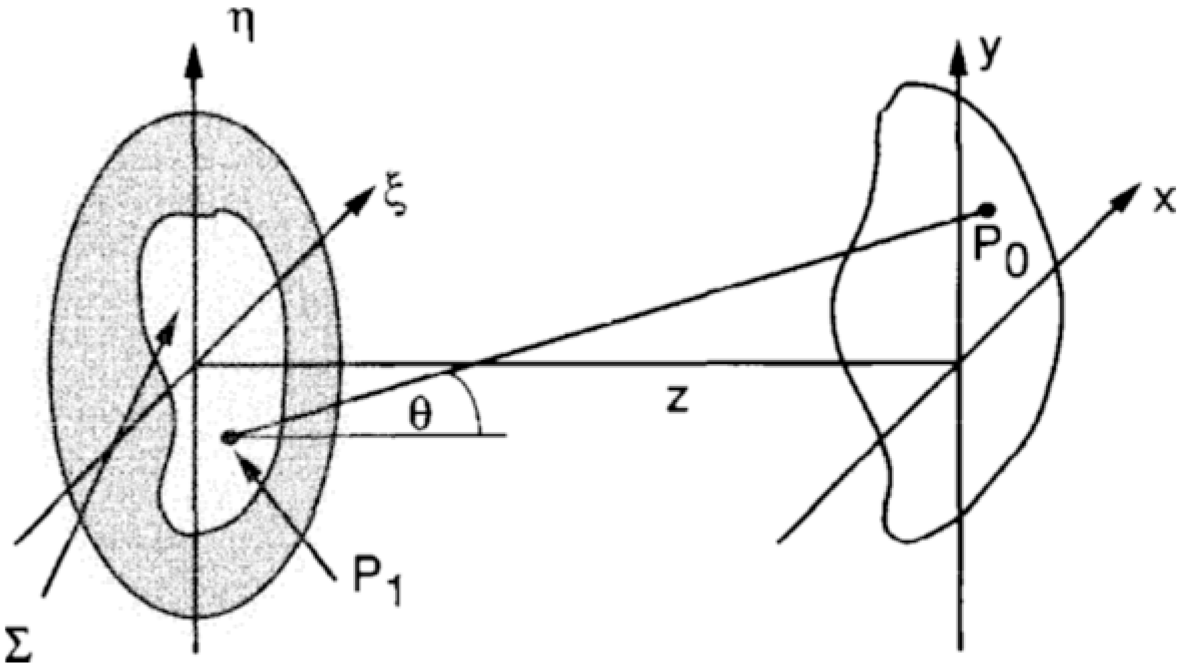
Principle of Wave Propagation



Huygens-Fresnel Principle

- Proposed by Huygens in 1678
- Every point in a light disturbance becomes a secondary source of spherical wave
- The sum of these secondary waves determines the form of the wave at subsequent times.
- Assumes the secondary waves travel only in the "forward" direction
- Qualitatively explains planar and spherical wave propagation, the laws of reflection and refraction, but not diffraction
- In 1818 Fresnel combined Huygens's principle with principle of interference
- Quantitatively explains rectilinear propagation of light and diffraction

Principle of Wave Propagation



Huygens-Fresnel Principle in Rayleigh-Sommerfeld solution

$$U(x,y)=\frac{1}{i\lambda}\iint_{\Sigma}U(\xi,\eta)\frac{\exp(ikr_{01})}{r_{01}}\cos\theta ds$$

$$\cos\theta=\frac{z}{r_{01}} \qquad r_{01}=\sqrt{(x-\xi)^2+(y-\eta)^2+z^2}$$

$$U(x,y)=\frac{z}{i\lambda}\iint_{\Sigma}U(\xi,\eta)\frac{\exp(ikr_{01})}{r_{01}^2}ds$$

Principle of Wave Propagation

Fresnel Approximation

$$z^3 \gg 2k\left[\left(x-\xi\right)^2+\left(y-\eta\right)^2\right]^2_{\max}$$

In denominator: $r_{01} \approx z$

In exponent:

$$r_{01}=\sqrt{\left(x-\xi\right)^2+\left(y-\eta\right)^2+z^2}=z\sqrt{1+\left(\frac{x-\xi}{z}\right)^2+\left(\frac{y-\eta}{z}\right)^2}\approx z\left[1+\frac{1}{2}\left(\frac{x-\xi}{z}\right)^2+\frac{1}{2}\left(\frac{y-\eta}{z}\right)^2\right]$$

$$U\left(x,y\right)=\frac{e^{ikz}}{i\lambda z}\iint_{\pm\infty}U\left(\xi,\eta\right)\exp\left\{-i\frac{2\pi}{\lambda z}\left[\left(x-\xi\right)^2+\left(y-\eta\right)^2\right]\right\}d\xi d\eta$$

Convolution

$$U\left(x,y\right)=\frac{e^{ikz}}{i\lambda z}e^{i\frac{k}{2z}\left(x^2+y^2\right)}\iint_{\pm\infty}U\left(\xi,\eta\right)e^{i\frac{k}{2z}\left(\xi^2+\eta^2\right)}\exp\left[-i\frac{2\pi}{\lambda z}\left(x\xi+y\eta\right)\right]d\xi d\eta$$

Fourier Transform

Principle of Wave Propagation

Fraunhofer Approximation

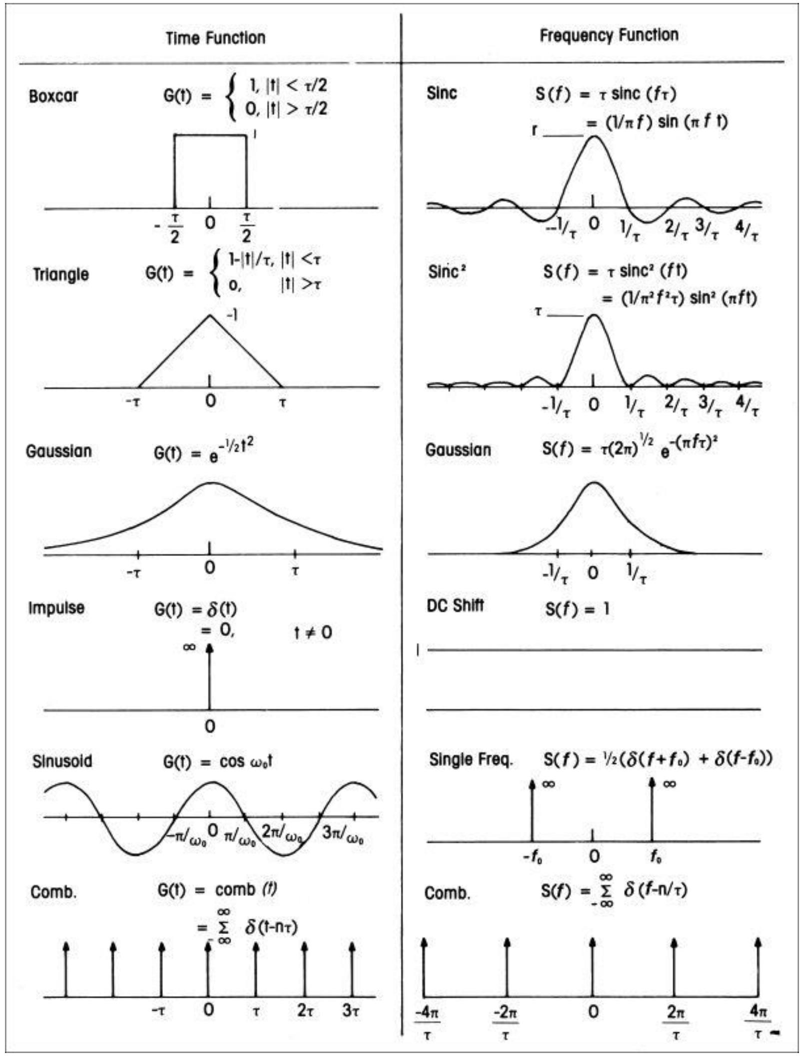
$$z \gg \frac{k}{2}\left(\xi^2+\eta^2\right)_{\max}$$

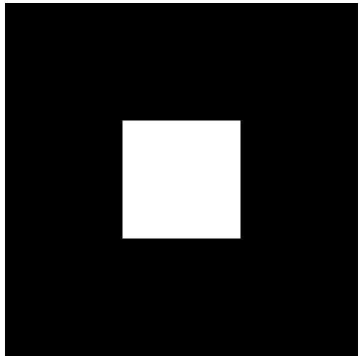
$$i\frac{k}{2z}\left(\xi^2+\eta^2\right) \to 0$$

$$U(x,y)=\frac{e^{ikz}}{i\lambda z}e^{i\frac{k}{2z}\left(x^2+y^2\right)}\iint_{\pm\infty} U(\xi,\eta)\exp\left[-i\frac{2\pi}{\lambda z}\left(x\xi+y\eta\right)\right]d\xi d\eta$$

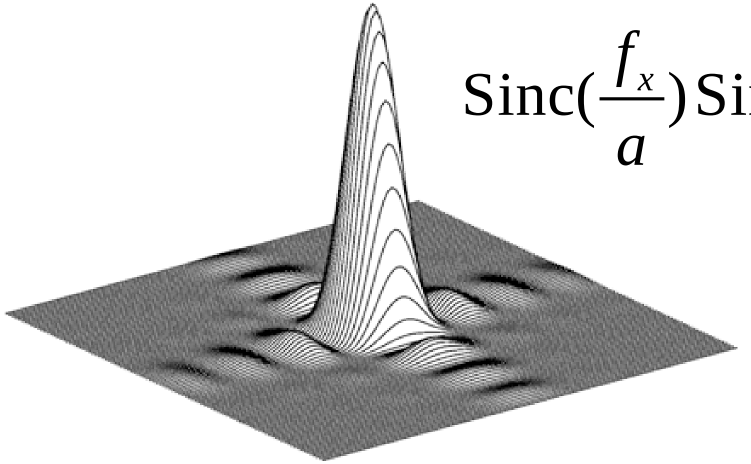
Fourier Transform

Example 2D Fourier Transforms

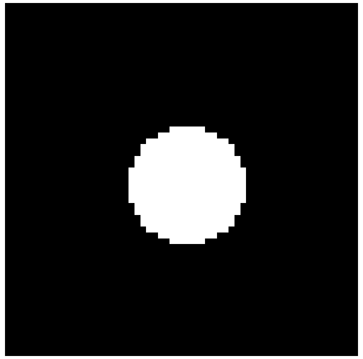




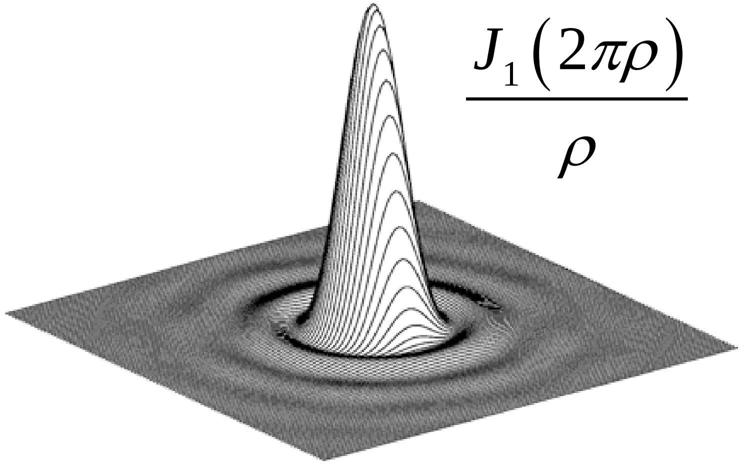
$\mathrm{Rect}(ax, by)$



$\mathrm{Sinc}(\frac{f_x}{a})\,\mathrm{Sinc}(\frac{f_y}{b})$



$\mathrm{Circ}(r)$



$$\frac{J_1(2\pi\rho)}{\rho}$$

Gaussian Beam Optics

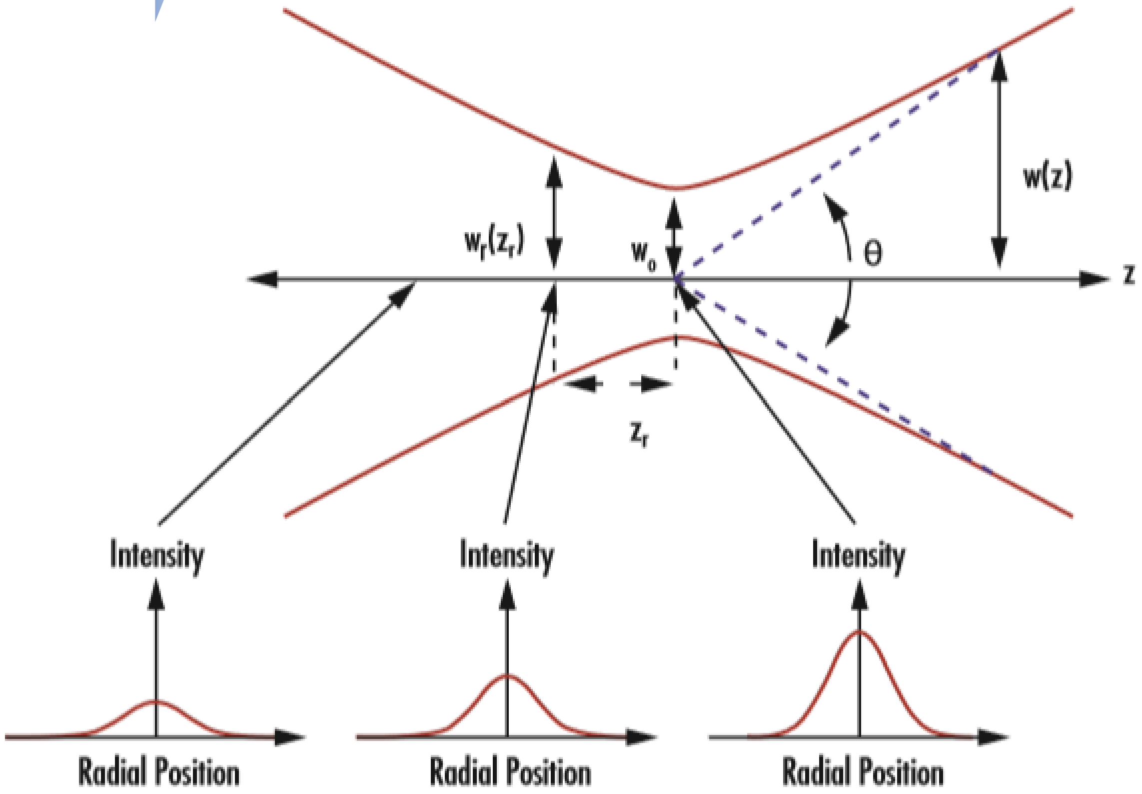
Helmholtz equation $$\left(\nabla^2 + k^2\right) A(P) = 0$$

Paraxial approximation $$A(P) = u(r)\exp(ikz)$$

$$\nabla_\perp^2 u + 2ik\frac{\partial u}{\partial z} = 0 \qquad \nabla_\perp^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

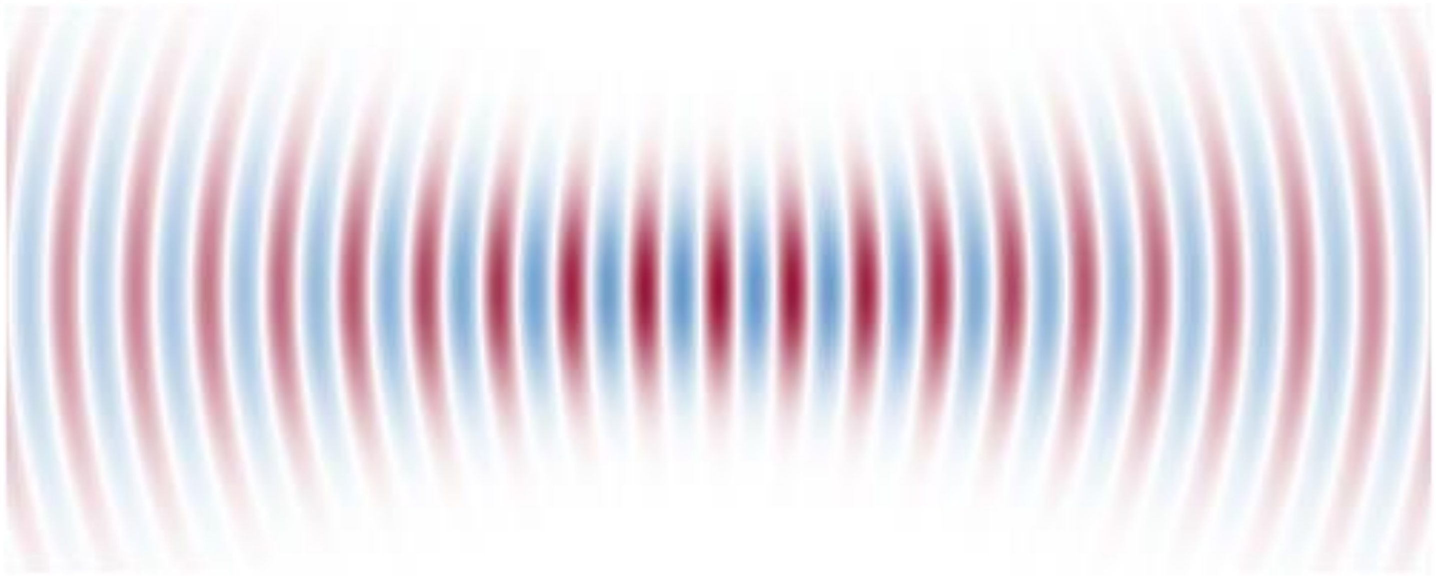
$$I(r,z) = I_0 \frac{w_0^2}{w(z)^2}\exp\left[-\frac{2r^2}{w(z)^2}\right]$$

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2} \qquad z_R = \frac{\pi w_0^2}{\lambda}$$

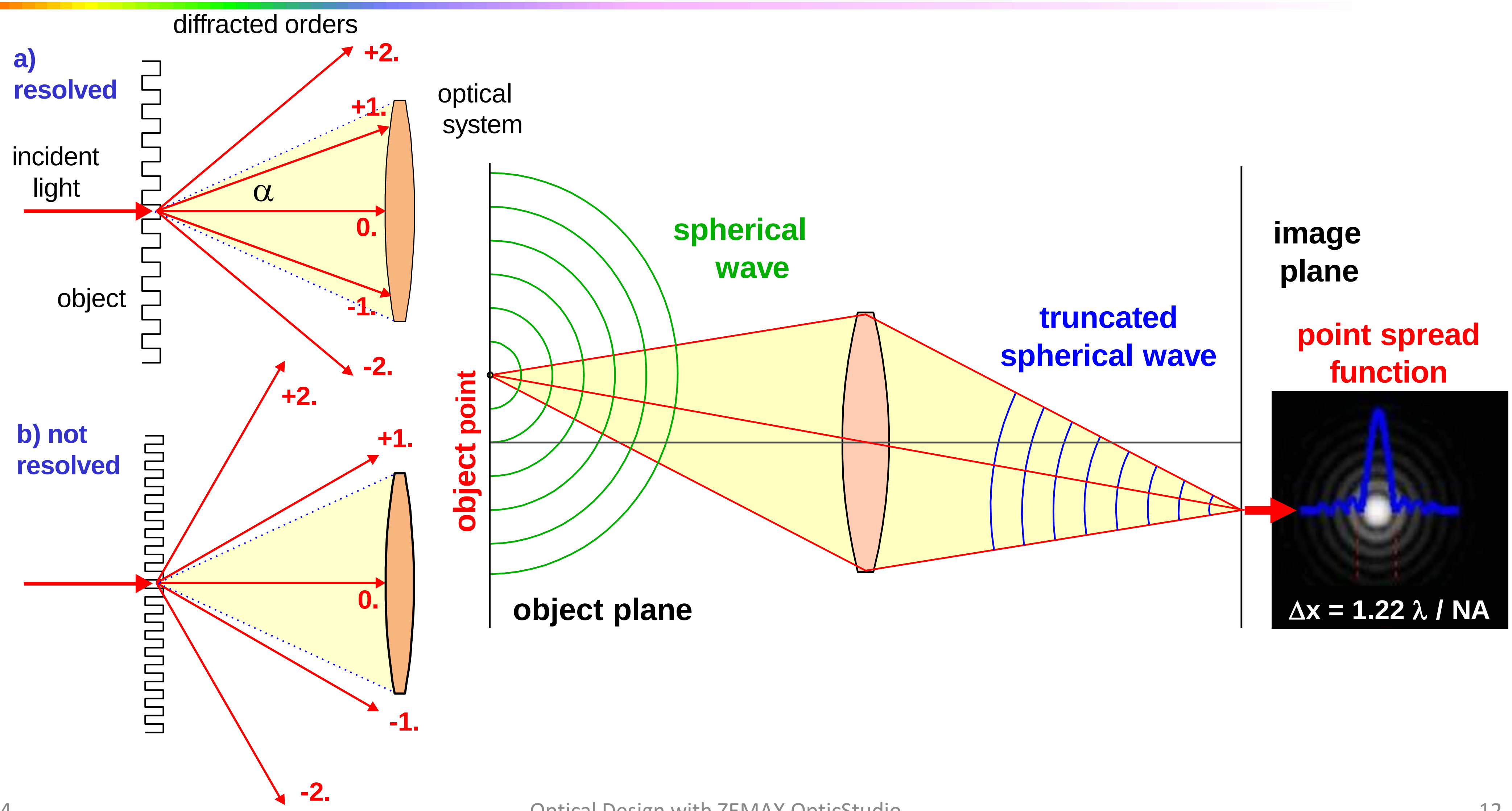


Gaussian Beam Propagation

$$\mathbf{E}(r,z) = E_0 \hat{\mathbf{e}} \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w(z)^2}\right] \exp(-ikz) \exp\left[-ik\frac{r^2}{2R(z)}\right] \exp\left[-i\psi(z)\right]$$



Lens as a Filter

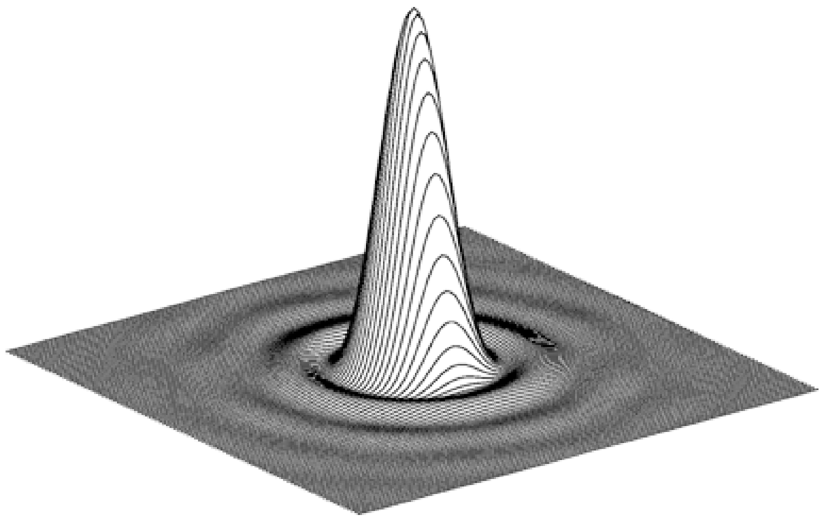


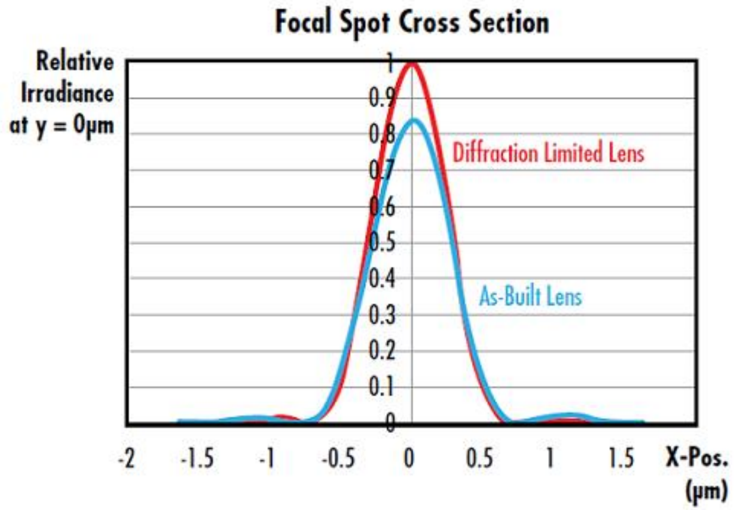
Modulation Transfer Function

- **MTF:** Quotient of the **contrast** (or **modulation depth**) in the image plane and the contrast in the object plane, for an object with a sinusoidal intensity distribution, as a function of **spatial frequency**
- Display modes of MTF often used in optical design:
  - MTF for different wavelengths, or an average over the spectrum
  - MTF for frequencies in radial (denoted by S) and tangential direction (denoted by T)
  - MTF (S and T) values for discrete frequencies as functions of defocus; this shows astigmatism and defocus
  - MTF (S and T) values for discrete frequencies as functions of the field height
  - The MTF of a system without aberrations is used as a benchmark

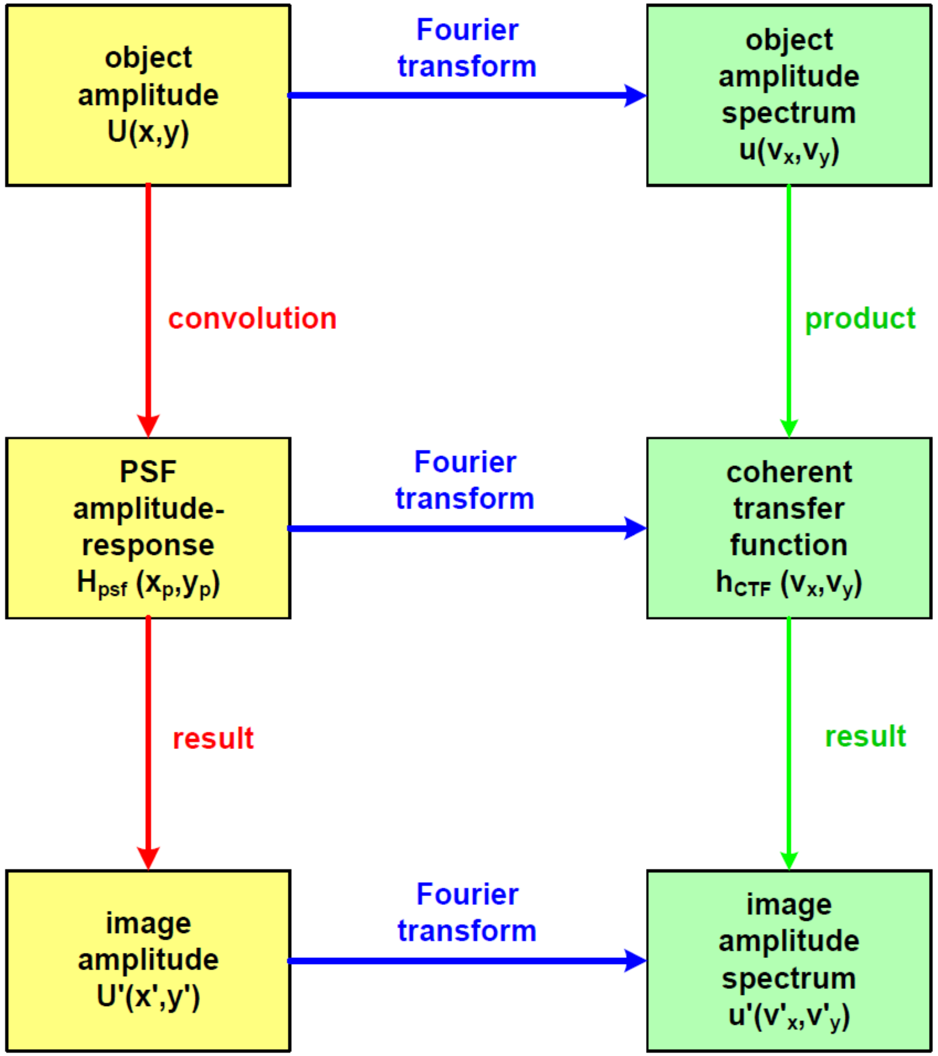
Point Spread Function

- **PSF:** Normalized intensity of the diffraction image pattern of a point object
- Useful diagnostic for optical systems with small aberrations
- Strehl number: the quotient of the intensity at the center of the PSF divided by the central intensity of an ideal PSF





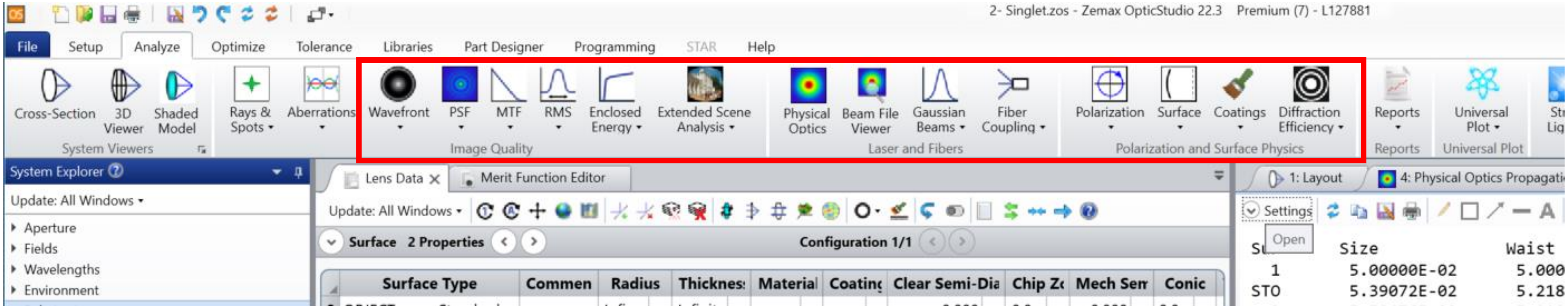
PSF vs MTF


object amplitude U(x,y)
Fourier transform
object amplitude spectrum u(vx,vy)
convolution
product
PSF amplitude-response Hpsf (xp,yp)
Fourier transform
coherent transfer function hCTF (vx,vy)
result
result
image amplitude U'(x',y')
Fourier transform
image amplitude spectrum u'(v'x,v'y)

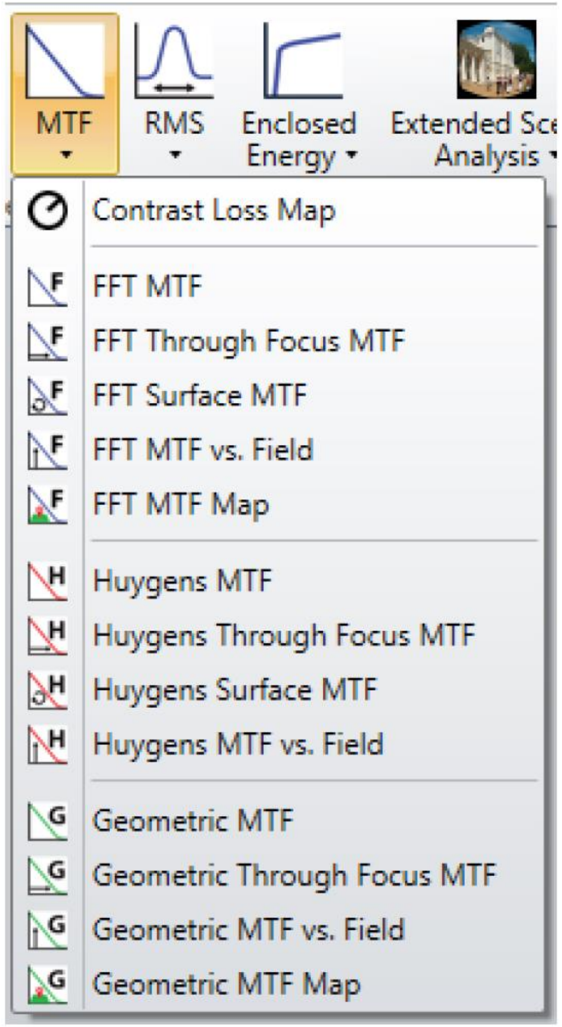
STI
MICRO-517

ZEMAX OpticStudio

ZEMAX OpticStudio: Physical Optics



ZEMAX OpticStudio: MTF



FFT MTF

- Computes the diffraction MTF for all field positions using an FFT algorithm
- Fast
- With assumptions
- Only accurate at F/# > 1.5

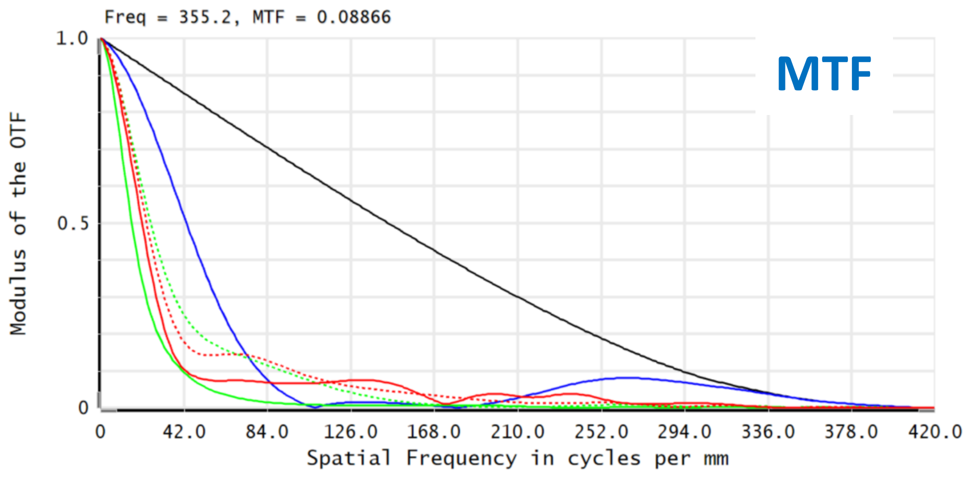
Huygens MTF

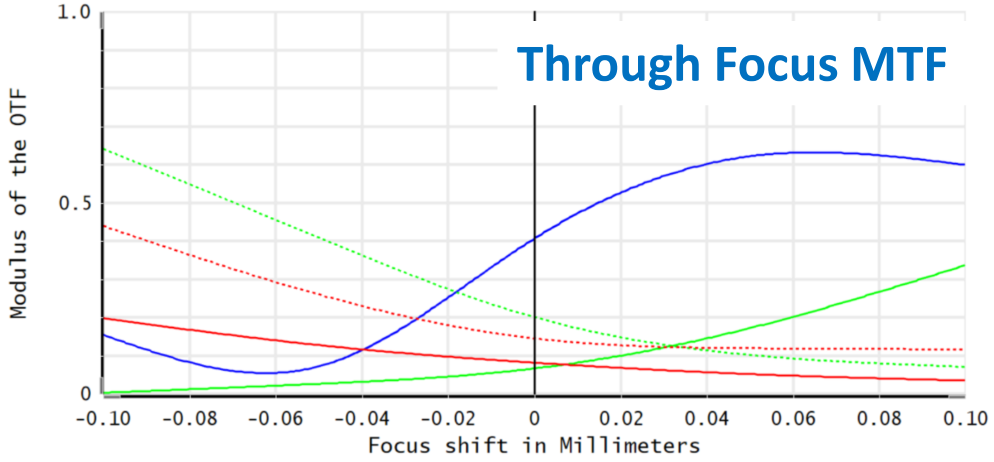
- Computes the diffraction MTF using a Huygens direct integration algorithm
- More accurate in most cases
- Slower

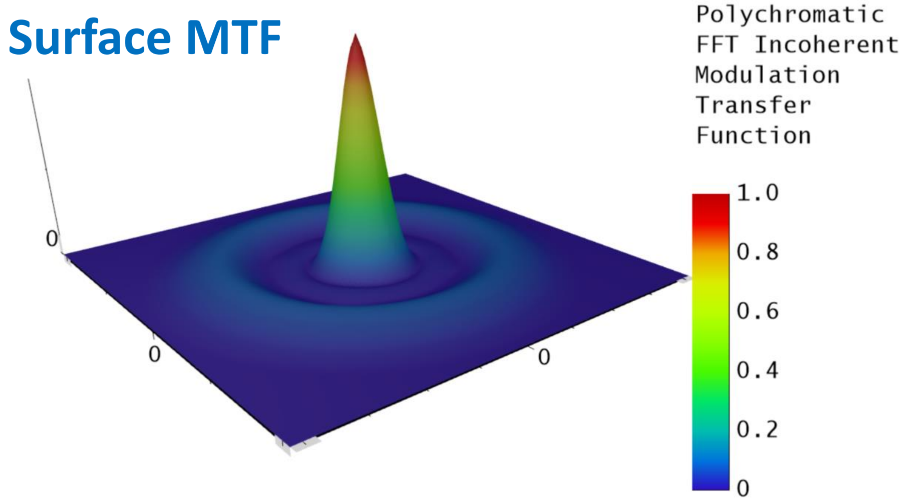
Geometric MTF

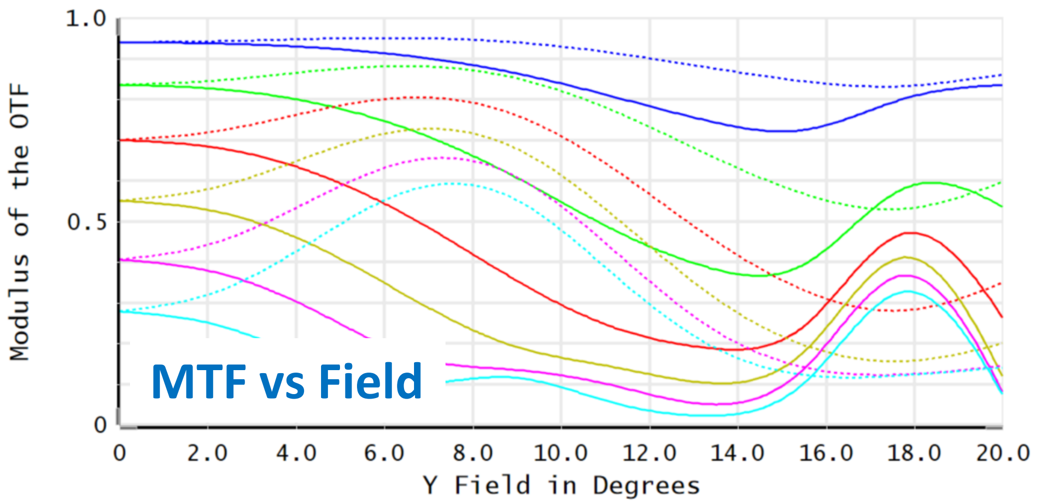
- Computes the geometric MTF, which is an approximation to the diffraction MTF based upon ray aberration data
- Very accurate for systems with large aberrations

ZEMAX OpticStudio: MTF

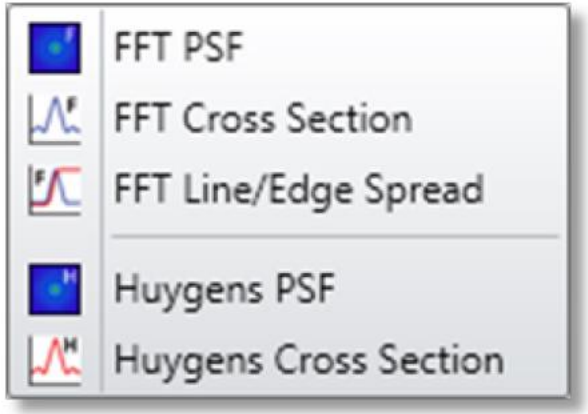


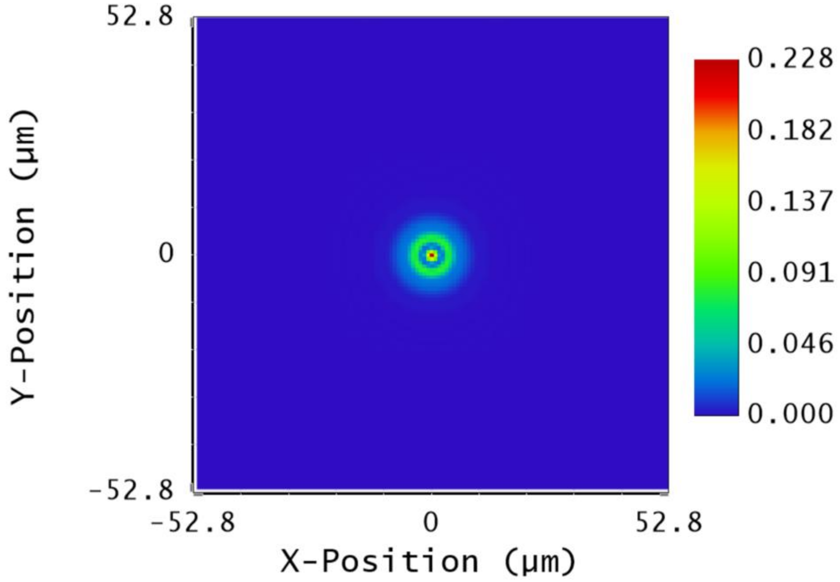






ZEMAX OpticStudio: PSF





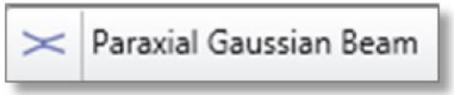
FFT PSF

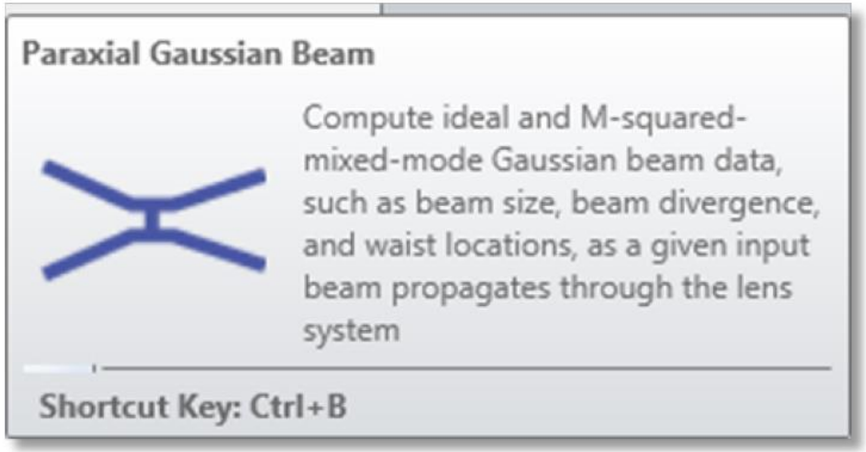
- Computes the diffraction point spread function (PSF) using the Fast Fourier Transform (FFT) method
- Fast
- With assumptions
- Only accurate at F/# > 1.5

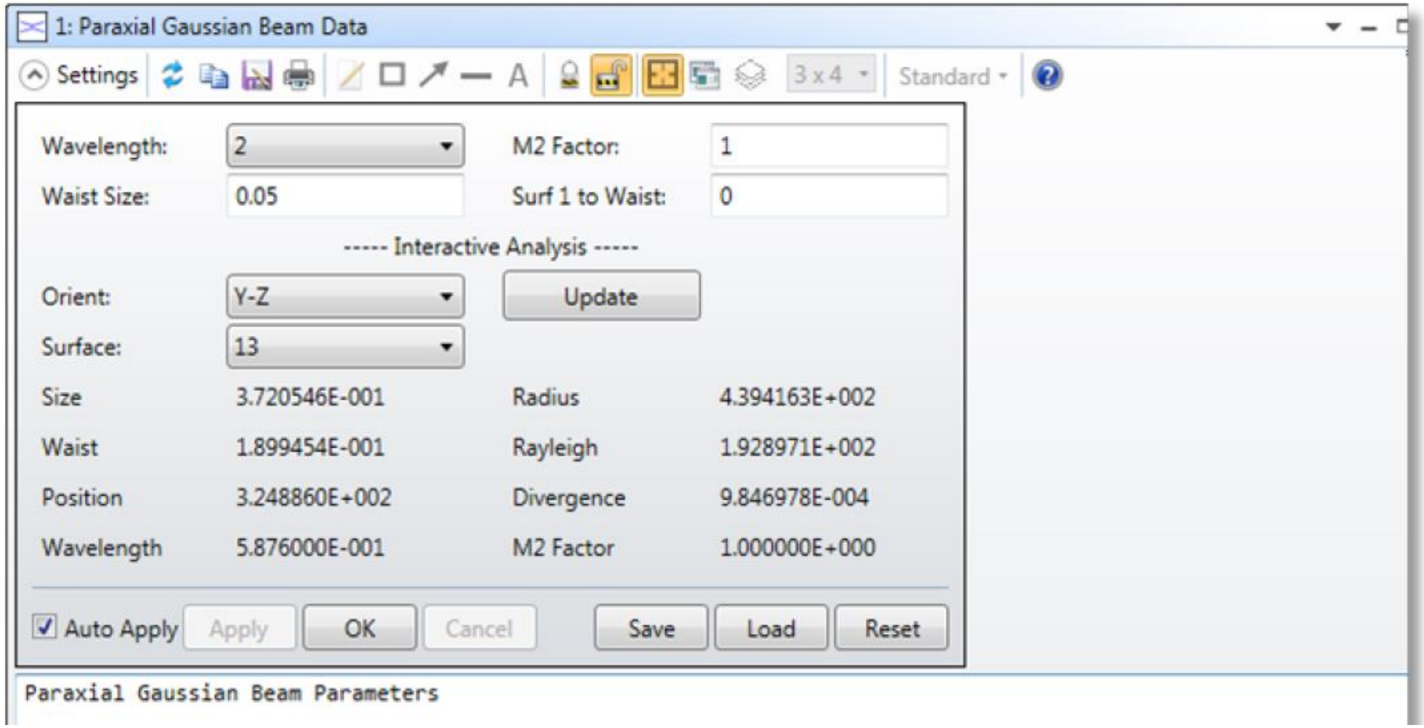
Huygens PSF

- Computes the diffraction PSF using direct integration of Huygens wavelets method
- Strehl ratio also computed
- More accurate
- More general
- Slower

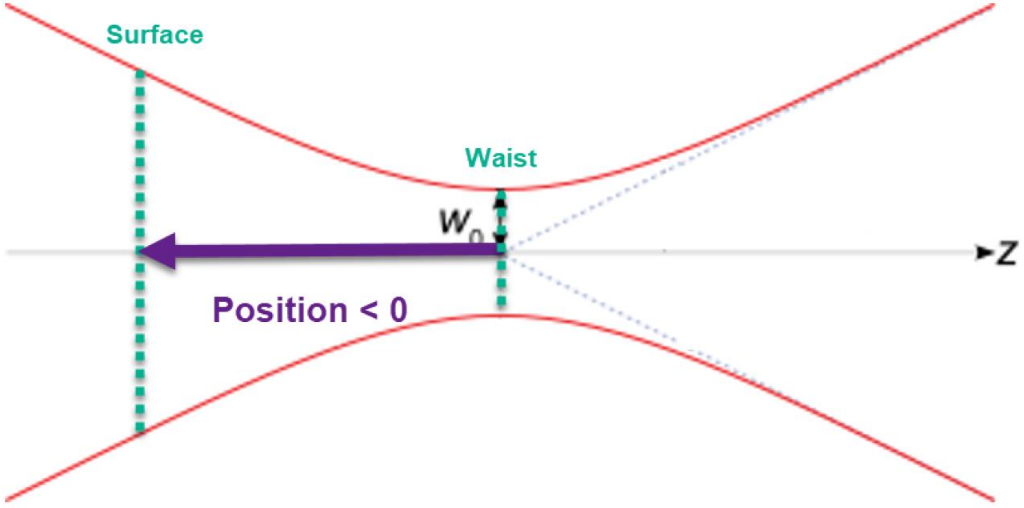
ZEMAX OpticStudio: Gaussian Beams

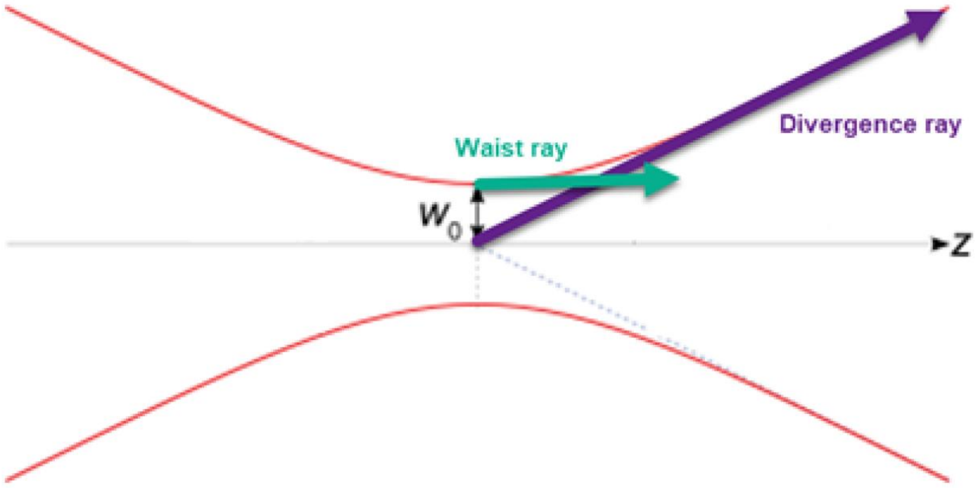




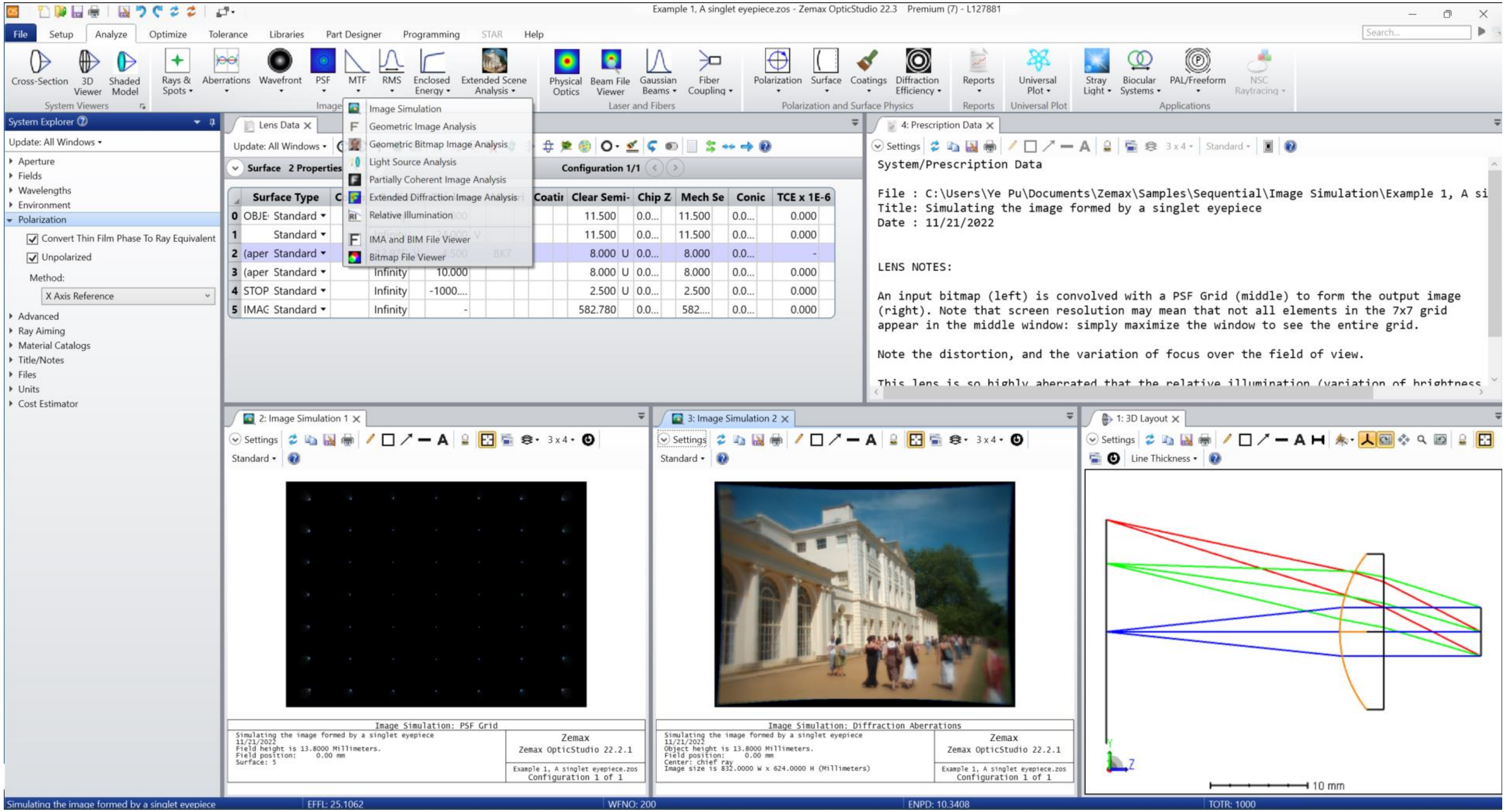


ZEMAX OpticStudio: Gaussian Beams





ZEMAX OpticStudio: Image Simulation



EPFL STI

MICRO-517

ZEMAX OpticStudio

Hands-on Time

Homework

To be announced