Review of Basic Principles in Optics, Wavefront and Wavefront Error

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Geometrical Optics

Relationships between pupil size, refractive error and blur
Optics of the eye: Depth of Focus

2 mm  4 mm  6 mm
Optics of the eye: Depth of Focus

Focused behind retina

In focus

Focused in front of retina

2 mm  4 mm  6 mm
Draw a cross like this one on a page. Hold it so close that it is completely out of focus, then squint. You should see the horizontal line become clear. The line becomes clear because you have used your eyelids to make your effective pupil size smaller, thereby reducing the blur due to defocus on the retina image. Only the horizontal line appears clear because you have only reduced the blur in the horizontal direction.
Physical Optics

The Wavefront
What is the Wavefront?

parallel beam = plane wavefront

converging beam = spherical wavefront
What is the Wavefront?

parallel beam = plane wavefront

ideal wavefront
defocused wavefront
What is the Wavefront?

parallel beam = plane wavefront

ideal wavefront

aberrated beam = irregular wavefront
What is the Wavefront?

- Diverging beam = spherical wavefront
- Aberrated beam = irregular wavefront
- Ideal wavefront
The Wave Aberration
What is the Wave Aberration?

diverging beam = spherical wavefront

wave aberration
Wave Aberration: Defocus
Wave Aberration: Coma

Wavefront Aberration

Wavefront Aberration

Wave Aberration: Coma
Wave Aberration: All Terms
Zernike Polynomials
Wave Aberration Contour Map
Breakdown of Zernike Terms

Coefficient value (microns)

-0.5 0 0.5 1 1.5 2

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Zernike term

1st order
2nd order
3rd order
4th order
5th order

- astig.
- defocus
- astig.
- trefoil
- coma
- coma
- trefoil
- spherical aberration
The Point Spread Function
The Point Spread Function, or PSF, is the image that an optical system forms of a point source.

The point source is the most fundamental object, and forms the basis for any complex object.

The PSF is analogous to the Impulse Response Function in electronics.
The Point Spread Function

The PSF for a perfect optical system is the Airy disc, which is the Fraunhofer diffraction pattern for a circular pupil.
Airy Disk

\[ \theta = \frac{q \cdot \pi}{\lambda / d} \]

angle subtended at the nodal point

wavelength of the light

pupil diameter
As the pupil size gets larger, the Airy disc gets smaller.
Point Spread Function vs. Pupil Size

1 mm  2 mm  3 mm  4 mm  
5 mm  6 mm  7 mm
Small Pupil
Larger pupil
Point Spread Function vs. Pupil Size

1 mm  2 mm  3 mm  4 mm  5 mm  6 mm  7 mm

Perfect Eye

Typical Eye
Demonstration
Observe Your Own Point Spread Function
Resolution
Unresolved point sources

↓

Rayleigh resolution limit

↓

Resolved
As the pupil size gets larger, the Airy disc gets smaller.
Keck telescope: (10 m reflector) *About 4500 times better than the eye!*
Convolution
Convolution
Simulated Images

20/20 letters

20/40 letters
MTF
Modulation Transfer Function
object: 100% contrast

image

contrast vs. spatial frequency
MTF: Cutoff Frequency

Rule of thumb: cutoff frequency increases by ~30 c/d for each mm increase in pupil size.
Modulation Transfer Function

vertical spatial frequency (c/d)

horizontal spatial frequency (c/d)

modulation
PTF
Phase Transfer Function
object

image

low

medium

high

spatial frequency

phase shift

-180

0

180

-180

spatial frequency
Relationships Between Wave Aberration, PSF and MTF
The PSF is the Fourier Transform (FT) of the pupil function

The MTF is the amplitude component of the FT of the PSF

The PTF is the phase component of the FT of the PSF
Conventional Metrics to Define Imagine Quality
Root Mean Square

\[ \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \]
Root Mean Square:
Advantage of Using Zernikes to Represent the Wavefront

\[
\sqrt{\text{astigmatism term} + \text{defocus term} + \text{astigmatism term} + \text{trefoil term} + \ldots}
\]
Strehl Ratio

diffraction-limited PSF

$H_{dl}$

actual PSF

$H_{eye}$
Modulation Transfer Function

Area under the MTF
Metrics to Define Image Quality

Other Metrics


Typical Values for Wave Aberration

Strehl Ratio

• Strehl ratios are about 5% for a 5 mm pupil that has been corrected for defocus and astigmatism.

• Strehl ratios for small (~ 1 mm) pupils approach 1, but the image quality is poor due to diffraction.
Typical Values for Wave Aberration

Population Statistics

- Trefoil
- Coma
- Spherical aberration

Zernike Term

(a) Avg Coeff Value (μm)

(b) Avg Coeff RMS (μm)
Typical Values for Wave Aberration

Change in aberrations with pupil size

- ○ Shack Hartman Methods
- □ Other Methods

Graph showing the change in rms wave aberration (microns) with pupil size (mm) for different methods and studies.
Other Optical Factors that Degrade Image Quality
Light scatter in the human eye

Stay tuned for
Thomas J. T. P. van den Berg
Retinal Sampling
Sampling by Foveal Cones

Projected Image

Sampled Image

20/20 letter

5 arc minutes
Sampling by Foveal Cones

*Projected Image*

*Sampled Image*

20/5 letter

5 arc minutes
Nyquist Sampling Theorem
Photoreceptor Sampling >> Spatial Frequency

nearly 100% transmitted
Photoreceptor Sampling = 2 x Spatial Frequency

nearly 100% transmitted
Photoreceptor Sampling = Spatial Frequency

nothing transmitted
Nyquist theorem: The maximum spatial frequency that can be detected is equal to _ of the sampling frequency.

foveal cone spacing ~ 120 samples/deg

maximum spatial frequency: 60 cycles/deg (20/10 or 6/3 acuity)
Thankyou!