Overview of UIS2 objectives

EVIDENT

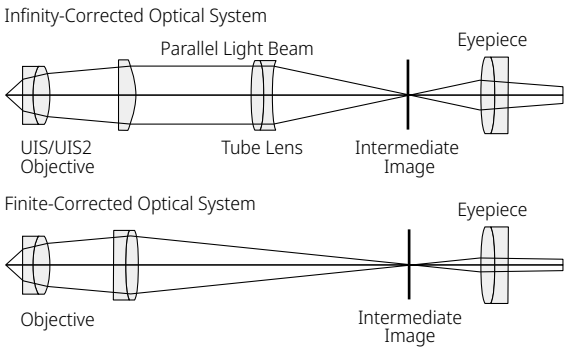
Introduction to UIS2 Optics

Take Advantage of Infinity-Corrected Optics

What Are Infinity-Corrected Optics?

The UIS2 infinity-corrected optical system is designed so that light passes from the specimen through the objectives without forming an image along the way. Instead, light travels in the form of parallel rays to the tube lens, is focused by the tube lens, and forms an intermediate image. Using finite-corrected optics, the intermediate image is formed by the objective without a tube lens.

Figure 1. Infinity-Corrected and Finite-Corrected Optical System Principles



Advantages of Infinity-Corrected Optics

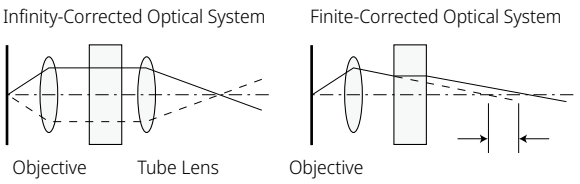
Infinity-corrected optics offer a number of advantages:

- There is no change in magnification, even when the distance between the objective and tube lens is altered.
- Because the total magnification remains constant, there is no image aberration — even when prisms or sliders are interposed between the objectives and the tube lens.

The advantages of UIS2 infinity-corrected optics are important when designing the ideal microscope optical system. With infinity-corrected optics, users can freely insert or remove intermediate attachments in the parallel rays of light between the objectives and tube lens, enabling the creation of user-specific or task-specific optical systems. To establish real flexibility with such a system, it is necessary to eliminate coma aberration. **

***In UIS2 objectives, the parfocal distance is 45 mm and the focal length of the tube lens is 180 mm.*

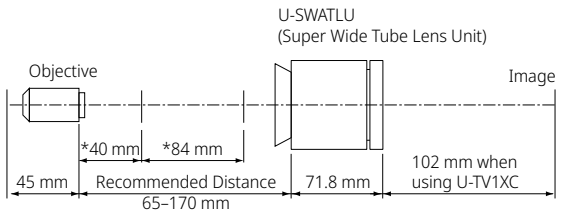
Figure 2. Advantages of an Infinity-Corrected Optical System



Basic Dimensions in the UIS2 Optical System

The UIS2 optical system corrects aberration with a dedicated tube lens and eyepiece; coma aberration and flatness are not degraded even when the tube lens's exit pupil position is modified by changing the objective and tube lens distance. This makes it possible to use a distance of 65 mm to 170 mm from the objective mounting position to the single port tube with lens. **See definition in the optical terminology section.*

Figure 3. Basic Dimensions of UIS2 Optical System



*Basic dimensions when our revolving nosepiece and illuminator are combined. When the position of the illuminator is changed, the illuminator's performance cannot be maintained.

Features of UIS2 Objectives

UIS2 objective lenses are compatible (in both screw diameter and optical performance) with the UIS optical system and offer the following features as compared to conventional objectives.

1. Wavefront Aberration Control

UIS2 objectives push the boundaries of performance with wavefront aberration control, high numerical apertures (NA), and long working distances. Our objectives are designed to provide excellent performance by minimizing the aberrations that reduce resolution.

****See definition in the optical terminology section.*

2. Objective Lenses with Image Parcentricity

Semi-apochromatic UIS2 objectives are designed to be parcentric. When a user changes objectives by rotating the nosepiece, the center of the field of view does not change on the digital camera (50X magnification or higher in the MPLFLN and LMPLFLN series objectives).

3. Improved Color Reproducibility

UIS2 objectives provide natural color reproduction without chromatic shifts using specially selected high-transmittance glass and advanced coating technology. These features provide high transmittance that is flat over a wide-band wavelength. The entire optical system, including the tube lens, is designed to reproduce the actual colors of specimens, so users know that they can obtain realistic images of specimens even without using a digital microscope camera.

4. Reduced Weight

UIS2 objectives (MPLFLN and LMPLFLN series) feature an aluminum objective barrel cover, reducing their weight to approximately 2/3 that of conventional objectives. This lightens the load on devices when the objectives are moved up and down, suppressing vibrations by lowering the inertia generated when users switch objectives.

5. Lead and Cadmium Free

UIS2 objectives are made from lead- and cadmium-free eco-glass.

UIS2 Objectives for Industrial Applications

Objective Abbreviation Guide

M PL(Plan) F L N - 1 0 0 B D

- **M:** Metallurgical (no cover)
- **MX:** High numerical aperture and long working distance for metallurgical use
- **LM:** Long working distance for metallurgical use
- **SLM:** Super long working distance for metallurgical use
- **LC:** Observation through substrate

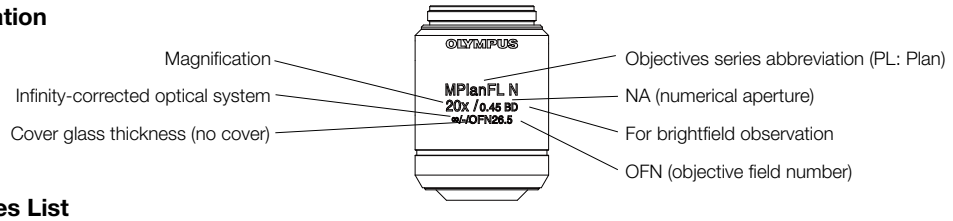
- **PL:** Plan: Corrects field curvature on the periphery of the image plane

- **None:** Achromat/ Effectively corrects chromatic aberration at 486 nm and 656 nm wavelengths
- **FL:** Semi-apochromat/ Corrects chromatic aberration that is in the middle of apochromat and achromat
- **APO:** Apochromat/ Effectively corrects chromatic aberration in the entire visible range (435-656 nm)

- **Number:** Objective magnification

- **None:** Brightfield
- **BD:** Brightfield/darkfield
- **IR:** Infrared
- **LCD:** Observation through LCD panels

Objective Notation



Objective Series List

Series	Magnification	BF	DF	DIC*1	POL	FL	OFN (Objective Field Number)	Remarks
MPLAPON	50/100	○		○U	○		26.5	
MPLAPON O	100	○			○	○	26.5	
MXPLFLN	20/50	○		○U	○	○*4	26.5	
MXPLFLN-BD	20/50	○	○	○U	○	○*4	26.5	
MPLFLN	1.25/2.5	○					1.25X: 22/2.5X: 26.5	We recommend using a polarizer and analyzer
	5/10/20/40*2/50/100	○		○U	○	○*3	26.5	
LMPLFLN	5/10/20/50/100	○		○L	○	○	26.5	
MPLN	5/10/20/50/100	○					22	
LCPLFLN-LCD	20/50/100	○		○L			26.5	For LCD
SLMPLN	20/50/100	○					26.5	
LMPLN-IR	5/10	○					22	For near-IR observation
LCPLN-IR	20/50/100	○					22	For near-IR observation
MPLFLN-BD	2.5/5/10/20/50/100/150	○	○	○U	○	○*3	26.5	
LMPLFLN-BD	5/10/20/50/100	○	○	○L	○	○	26.5	
MPLN-BD	5/10/20/50/100	○	○				22	
WLI100XMRTC	100X	○					22	Mirau objective

*1 U-DICR DIC prism: UM/LM position fixed.
*2 40X: BF only *3 5–20X: UV excitation also possible. *4 50X: UV excitation also possible.
Observation method: BF: Brightfield; DF: Darkfield; DIC: Differential interference contrast; POL: Polarized light; FL: Fluorescence

Features of Each Objective Series

● MPLAPON series: M Plan Apochromat
This series of plan-apochromat objectives corrects chromatic aberrations at optimal levels. Evident guarantees* the optical performance (correction for wavefront aberration) with a Strehl ratio** of 95% or better. These objectives can be used with the BXC-FSU autofocus sensing unit.

● MPLAPON100XO2: M Plan Apochromat
This plan-apochromat objective is designed for oil immersion*** and features a numerical aperture of 1.45. The objective provides excellent chromatic aberration correction and high resolving power.

● MXPLFLN series: MX Plan Semi Apochromat
MX plan semi-apochromat objectives combine an improved numerical aperture with a long distance. Their 3 mm working distance enables users to move the stage with less chance of the objective hitting the sample, improving wafer inspection throughput.

● MPLFLN series: M Plan Semi Apochromat
This series of plan semi apochromat objectives delivers high-level correction for chromatic aberration. The eight objectives in this series offer magnifications ranging from 1.25X to 100X and a minimum working distance of 1 mm (except 40X). Since the exit pupil position of the 5X–100X objectives is standardized, the position of the DIC prism does not have to be switched when changing the magnification (40X is not applicable to DIC observation). For very low magnifications (1.25X, 2.5X), use the objectives with an analyzer, polarizer, and reflected light illuminator.

● LMPLFLN series: Long Working Distance M Plan Semi Apochromat
This series of long working distance plan semi apochromat objectives delivers high-level correction for chromatic aberration. Because of the long working distance, these objectives are suitable for observing larger samples. Since the exit pupil position of the 5X–100X objectives is standardized, the position of the DIC prism does not have to be switched when changing the magnification.

● MPLN series: M Plan Achromat
Plan achromat objectives provide excellent image flatness up to OFN22.

● LCPLFLN-LCD series: LCD Long Working Distance LC Plan Semi Apochromat
These objectives are designed for making observations through LCD panels and other samples that have a glass substrate. The correction collar provides aberration correction that can be matched to the thickness of the glass.

● SLMPLN series: Super Long Working Distance M Plan Achromat
These are high-magnification plan achromat objectives with a super long working distance. Three magnifications, 20X, 50X, and 100X, are available. For 5X or 10X objectives, select from the LMPLFLN series.

● LMPLN-IR series: IR Long Working Distance M Plan Achromat
This series is designed for near-infrared microscopy, which is typically used to view the internal structure of silicon wafers.

● LCPLN-IR series: IR Long Working Distance LC Plan Achromat
This series is designed for near-infrared microscopy, which is typically used to view the internal structure of silicon wafers. These objectives have a correction collar to correct for aberrations based on the thickness of the silicon or glass substrate.

● MPLFLN-BD series: M Plan Semi Apochromat BD
This series of plan semi apochromat objectives provides high-level correction for chromatic aberration with a minimum working distance of 1 mm. Since the exit pupil position of the 5X–150X objectives is standardized, the position of the DIC prism does not have to be switched when changing the magnification.

● LMPLFLN-BD series: Long Working Distance M Plan Semi Apochromat BD
This series of long working distance plan semi apochromat objectives provides high-level correction for chromatic aberration and are suitable for observing samples with height or varying topography. Since the exit pupil position of the 5X–100X objectives is standardized, the position of the DIC prism does not have to be switched when changing the magnification.

● MPLN-BD series: M Plan Achromat BD
This series of plan achromat objectives provides excellent image flatness up to OFN22.

● WLI100XMRTC: White Light Interferometry Objective
This objective is designed to be used with Mirau-style white light interferometers and tolerates high temperatures. The objective has a working distance of 0.7 mm and an optimized NA of 0.8 that provides improved light gathering.

**Measurement guarantee assessed with an Evident interferometer for transmitted wavefront measurement under the following conditions: a temperature of 23 °C + 1 °C; measurements made within the 97% range of the pupil diameter.*

***Strehl ratio: Indicates in percent (%) the ratio of the proportion of light that an actual optical system can concentrate with respect to the proportion of light concentrated in the image plane (central intensity) by an ideal, aberration-free optical system, with the latter serving as 100%. A higher percentage indicates a higher quality optical system.*

****Specified oil: IMMOIL-F30CC*

UIS2 Objectives for Life Science Applications

World-leading optics

Objective Abbreviations Guide

U PL (Plan) FL N 60X OI PH

U: Universal objectives for fluorescence (U/BG) and DIC
L: Long working distance
C: Tissue culture observations through bottles and dishes
M: For no cover observation
***XL:** Extra large; parfocal length exceeds 45 mm (e.g. XLUMPLFL20XW 75 mm)

PL (or PLN): Plan: Corrects field curvature of the periphery on the image plane
None: Non-Plan

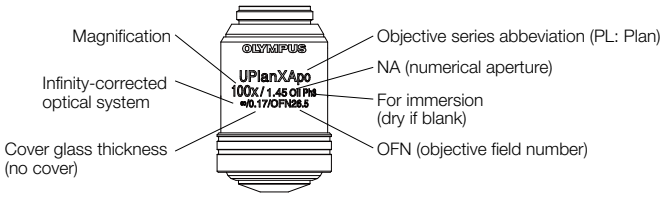
ACH: Achromat/ Effectively corrects chromatic aberration at 486 nm and 656 nm wavelengths
FLN: Semi-apochromat/ Corrects chromatic aberration that is in the middle of apochromat and achromat
APO: Apochromat/ Effectively corrects chromatic aberration in the entire visible range (435-656 nm)
SAPO: Super apochromat/ Effectively corrects chromatic aberration in the visible to near infrared range (435-1000 nm)
XAPO: Extended apochromat/ Effectively corrects chromatic aberration in the visible to infrared range (400 to 1000 nm)

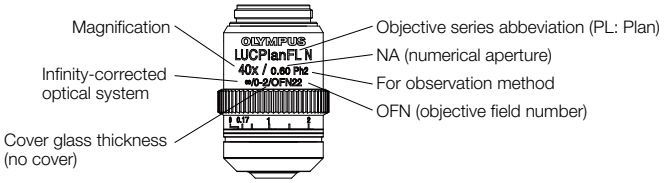
Number: Objective magnification

None: Dry
O: Oil immersion
W: Water immersion
S: Silicone immersion
OI: Oil immersion with iris

None: Brightfield
P: Polarizing
PH: Phase contrast
PHP: Pre-centered phase contrast
RC: Relief contrast
340 : High-transmission at 340 nm wavelength

Objective Notation





Objective Series List

Objective series for standard biological samples

Series	Magnification	BF	DF	DIC*	POL	FL	OFN (Objective Field Number)	Remarks
UPLXAPO	4X/10X/20X/40X/40XO/60XO/100XO	○	10X/20X	○ (except 4X)	○	○	26.5	
UPLSAPO	60XW	○		○	○	○	26.5	
PLAPON	1.25X/2X	○					26.5	
UPLFLN	4X/10X2/20X/40X/40XO/60X/60XOI/100XO2/100XOI2	○	10X2/20X/40X/60XOI/100XOI2	○ (except 4X)	○	○	26.5	
PLFLN	100X	○				○	26.5	
PLN	2X/4X/10X/20X/40X/50XOI/100XO	○	10X/20X/40X/50XOI	10X/20X/40X/50XOI		○	22	
UPLFLN-PH	4XPH/10X2PH/20XPH/40XPH/60XOIPH/100XO2PH	○	10X2PH/20XPH/40XPH/60XOIPH			○	26.5	
PLN-PH	10XPH/20XPH/40XPH/100XOPH	○	○ (except 100XOPH)				22	
UPLFLN-P	4XP/10XP/20XP/40XP/100XOP	○	10XP/20XP/40XP	○ (except 4XP)	○	○	26.5	
PLN-P/ACHN-P	4XP/10XP/20XP/40XP/100XOP	○	10XP/20XP/40XP		○	○	22	

*These objectives are suitable for standard biological samples embeded on a glass slide with a 0.17 mm cover slip and are mainly used with upright microscopes.

Objective series for cultured samples

Series	Magnification	BF	DF	DIC	POL	FL	OFN (Objective Field Number)	Remarks
LUCPLFLN	20X/40X/60X	○	○	○	○	○	22	
LUCPLFLN-RC/ UCPLFLN-RC	10XRC/20XRC/40XRC	○	○			○	22	
LUCPLFLN-PH/ UCPLFLN-PH	10XPH/20XPH/40XPH/60XPH	○	○			○	22	
CPLN-PH/ LCACHN-PH	10XPH/20XPH/40XPH	○	○				22	
CPLN-RC/ LCACHN-RC	10XRC/20XRC/40XRC	○	○				22	

These objectives are suitable for cultured tissue/cell observation in a dish, bottle, or micro plate and are mainly used with inverted microscopes.

Objective series for special applications

Series	Magnification	BF	DF	DIC	POL	FL	OFN (Objective Field Number)	Remarks
LUMPLFLN/ UMPLFLN	10XW/20XW/40XW/60XW	○	10XW/20XW	○	○	○	26.5	
XLUMPLFLN	20XW	○		○		○	22	Parfocal length 75 mm
APON 340	20XW/40XO/40XW	○	20XW/40XW	○	○	○	22	

Features of Each Objective Series

- UPLXAPO: Extended Apochromat
- UPLSAPO: Universal Plan Super Apochromat
- PLAPON: Plan Apochromat
- UPLFLN: Universal Plan Semi Apochromat/Plan Semi Apochromat
- PLN: Plan Achromat
- UPLFLN-PH UPlanFl-P Universal Plan Semi Apochromat for Phase Contrast
- PLN-PH: Plan Achromat for Phase Contrast
- UPLFLN-P: UPlanFl-P Universal Plan Semi Apochromat for Polarization.
- PLN/ACHN-P: Achromat for Polarization.
- LUCPLFLN, UCPLFLN: Long Working Distance Universal Plan Semi Apochromat
- LUCPLFLN/UCPLFLN-RC: Long Working Distance Universal Plan Semi Apochromat for Relief Contrast
- LUCPLFLN/UCPLFLN-PH: Long Working Distance Universal Plan Semi Apochromat for Phase Contrast
- CPLN/LCACHN-PH: Culture Specimen Objectives for Phase Contrast
- CPLN/LCACHN-RC: Culture Specimen Objectives for Relief Contrast
- LUMPLFLN/UMPLFLN: No Cover Water Immersion for Fixed Stage Upright Microscope
- XLUMPLFLN: No Cover Water Immersion for Fixed Stage Upright Microscope
- APON 340: Universal Apochromat

Optical Terminology

1. FN and Practical Field of View

The field number (FN) is the size (in mm) of the eyepiece diaphragm, which defines the viewable area of a specimen. The diameter on the sample plane that can actually be viewed through the eyepiece is known as the practical field of view (FOV) and is determined by the following formula:

$$FOV = \frac{\text{Eyepiece FN}}{\text{Objective Magnification}} \text{ (mm)}$$

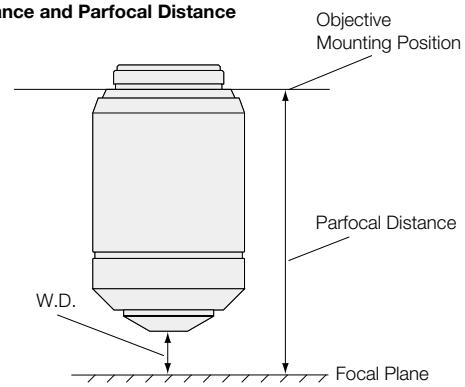
2. Working Distance

The working distance (W.D.) is the distance between the front edge of the objective and the specimen surface (or the surface of the cover glass when using a cover glass objective) when the specimen is in focus.

3. Parfocal Distance

The parfocal distance is the distance between the objective mounting plane and the specimen. In UIS2/UIS objectives, the parfocal distance is designed to be 45 mm.

Working Distance and Parfocal Distance



4. Relationship Between the Objective's Focal Length and Magnification

The magnification indicated for a UIS2/UIS objective is the value when the focal length of the tube lens is 180 mm.

$$M_{(ob)} = \frac{\text{Focal Length of Tube Lens}}{f}$$

$M_{(ob)}$: Objective magnification
f: Objective's focal length

5. Total Magnification

5.1 Observation Through Eyepiece (binocular observation)

$$M_{(bino)} = M_{(ob)} \times M_{(oc)}$$

$M_{(bino)}$: Total magnification for binocular observation
$M_{(ob)}$: Objective magnification
$M_{(oc)}$: Eyepiece magnification

5.2 Monitor Observation

●Total Magnification for Monitor

$$M_{(monitor)} = M_{(ob)} \times M_{(camera\ adapter)} \times \text{Moniter Magnification}^*$$

$M_{(monitor)}$: Total Magnification on the Monitor
$M_{(ob)}$: Objective Magnification
$M_{(camera\ adapter)}$: Projected magnification for camera adapter including photo eyepiece
(See Figure 1.)

**See Figure 3 for "monitor magnification."*

●Practical Field of View for Monitor Observation

$$\text{Practical Field of View for Monitor Observation} = \frac{\text{Image Device Size}^*}{M_{(ob)} \times M_{(camera\ adapter)}}$$

$M_{(ob)}$: Objective Magnification
$M_{(camera\ adapter)}$: Projected magnification for camera adapter including photo eyepiece
(See Figure 1 for projected magnifications.)

**See Figure 2 for image device size.*

Figure 1 Camera Adapter and Projection Magnifications

Camera Adapter (projection lens)	Projection Magnification
U-TV1X-1 + Camera Mount Adapters	1X
U-TV1XC	1X
U-TV0.63XC	0.63X
U-TV0.5XC-3	0.5X
U-TV0.35XC-2	0.35X

Figure 2 Imaging Device Size

Camera Format	Diagonal (mm)
1/3 in.	6.0
1/2 in.	8.0
2/3 in.	11.0
1 in.	16.0

The above table is for standard image device sizes.
Check your device size for precise calculation.

Figure 3 Imaging Device Size and Monitor Magnifications

Camera Format	Monitor Size (diagonal)				
	10 in.	15 in.	17 in.	19 in.	21"
1/3 in.	42.3X	63.5X	72.0X	80.4X	88.9X
1/2 in.	31.8X	47.6X	54.0X	60.3X	66.7X
2/3 in.	23.1X	34.6X	39.3X	43.9X	48.5X
1 in.	15.9X	23.8X	27.0X	30.1X	33.3X

Example
What is the total magnification of a monitor when a 50X objective, U-TV0.5XC camera adapter, 2/3 in. camera, and 21 in. monitor are used?

•Total magnification on the monitor:
M(ob) = 50X, M (camera adaptor) is 0.5X from Figure 1, and the monitor magnification is 48.5X from Figure 3.
M(monitor observation) = M(ob) × M(camera adaptor) × monitor magnification = 50 × 0.5 × 48.5 = 1213X

•Practical field of view for observation (horizontal side):
M(ob) = 50X, M(camera adaptor) is 0.5X (from Figure 1), and the horizontal side of a 2/3 in. imaging device is 8.8 mm (from Figure 2)

$$\text{Practical Field of View for Observation} = \frac{\text{Image Device Size}}{M_{(ob)} \times M_{(\text{camera adaptor})}}$$

$$= \frac{8.8\ (\text{mm})}{50 \times 0.5} = 352\ \mu\text{m}$$

6. Numerical Aperture (NA)

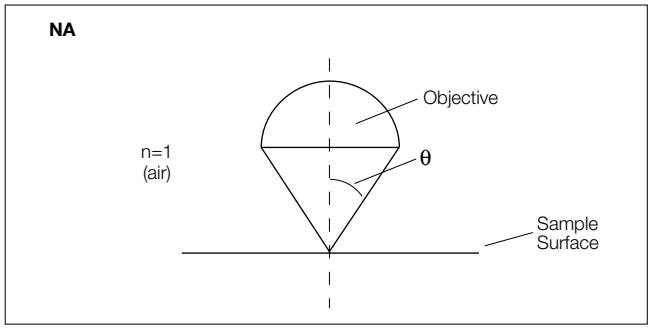
The numerical aperture is a key factor to the performance of an objective (resolving power, depth of field, and brightness). The NA is determined by the following formula:

$$NA = n \times \sin\Theta$$

n=The refraction rate of the medium between the specimen and objective. (Air: n=1, oil: n=1.515)
Θ: The angle made by the optical axis and refraction of the light farthest from the center of the lens.

The visual field brightness (B) of the microscope is determined by the following formula in relation to the objective magnification (M). The larger the NA and the lower the objective magnification, the brightness will increase by a factor of the second power.

$$B \propto \frac{NA^2}{M^2}$$



7. Resolving Power

The resolving power of an objective is measured by its ability to differentiate two lines or points in an object. The greater the resolving power, the smaller the minimum distance between two lines or points that can still be distinguished. The larger the NA, the higher the resolving power.

Resolving Power Formula

The following formula is generally used for determing resolution.

$$\varepsilon = 0.61 \times \frac{\lambda}{NA}\ \text{(Reyleigh formula)}$$

λ: Wavelength or radiation in use
(λ=0.55 μm is used for visible light.)
NA: Objective NA

Example
MPLFLN100X (NA=0.90), λ=0.55 μm

$$\varepsilon = 0.61 \times \frac{\lambda}{NA} = \frac{0.3355}{NA} = \frac{0.3355}{0.90} = 0.37\ \mu\text{m}$$

8. Depth of Field of Microscope

The depth of field refers to the depth of the specimen layer that is in sharp focus at the same time, even if the distance between the objective and the specimen plane is changed when observing and imaging the specimen plane using the microscope. Because human eyes are individually different in the ability to adjust their focus, each person's perception of the depth of field varies.
At present, the Berek formula is generally used because it gives a depth of field value that often coincides with the depth of field obtained through experiments.

Depth of Field Formula

Visual Observation (Berek formula)

$$\pm DOF = n\left(\frac{\omega \times 250{,}000}{NA \times M} + \frac{\lambda}{2\,(NA)^2}\right)(\mu m)$$

DOF: Depth of Field

ω: Resolving Power of Eyes 0.0014
(visual angle 5 arc minutes)
M: Total Magnification
(objective magnification x eyepiece magnification)

$$\rightarrow \pm DOF = n\left(\frac{350}{NA \times M} + \frac{0.275}{NA^2}\right)(\lambda = 0.55\ \mu m)$$

This indicates that the depth of field becomes smaller as the numerical aperture becomes larger.

Example
With MPLFLN100X (NA=0.90), WHN10X:

$$\pm DOF = 1 \times \left(\frac{350}{0.90 \times 1{,}000} + \frac{0.275}{0.81}\right) = 0.39 + 0.34 = 0.73\ \mu m$$

Camera

In the case of a camera, the depth of field will vary according to the number of pixels of the camera, optical magnification, and numerical aperture. The above-mentioned formula is used as a rough guide only.

9. Aberrations

A difference between an ideal image and the actual image that passes through an optical system is called an aberration.

9.1 Requirements for Ideal Image Formation

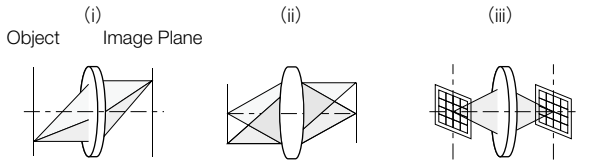
The following three requirements must be satisfied to form an image with no aberrations, or an ideal image.

(i) All the light rays coming from a single point and passing through an image formation optical system converge on a single point.

(ii) Image points, which correspond to object points on the same plane perpendicular to the optical axis, are present on the same plane.

(iii) The planar shape of an object and the planar shape of an image that are on the same plane perpendicular to the optical axis have a similar relation.

Figure 9-1 Requirements for Ideal Image Formation



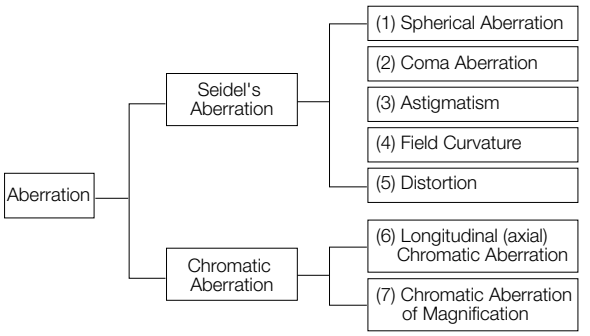
In an actual optical system, however, it is very difficult to strictly meet the requirements for ideal image formation, and this causes aberrations that interfere with image-forming performance.

9.2 Classification of Aberrations

Aberrations that interfere with image-forming performance are classified as shown below in Figure 9-2.

Seidel's Aberration = "Expansion of a Point Image" + "Curvature of the Image Plane" + "Deformation"

Figure 9-2 Classification of Aberrations



Types (1) to (3) correspond to "expansion of a point image" that goes against requirement (i) for ideal image formation in Figure 9-1. Type (4) corresponds to "curvature of image plane" that goes against requirement (ii) in Figure 9-1.

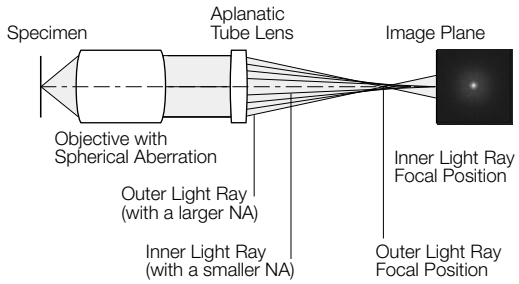
Type (5) corresponds to "deformation" that goes against requirement (iii) in Figure 9-1.

Types (6) and (7) correspond to the "color blur" of images caused by characteristics of glass materials used for the optical system. "Expansion of a point image" can also be expressed by wavefront aberration, which regards the light as waves and takes into account the phase to include the influence of diffraction.

(1) Spherical Aberration

When light rays coming out of an axial object point enter a lens, the light rays with a larger numerical aperture (NA) are subjected to stronger refraction power and cross the optical axis in positions further away from the ideal image formation position. The aberration caused by different image forming positions due to the differences in NA of axial light rays is called spherical aberration. Spherical aberration is proportional to NA to the third power.

Figure 9-3 Spherical Aberration

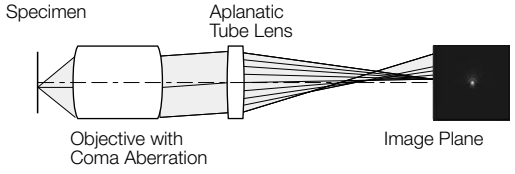


Typically, objectives with a larger NA have better resolution but worse spherical aberration. Our advanced design and manufacturing techniques have realized good optical performance even with a large numerical aperture.

(2) Coma Aberration

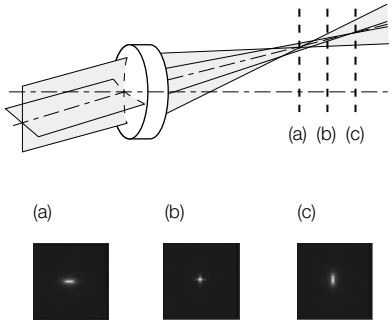
Even though spherical aberration is compensated to be very small, there are cases where light rays coming out of an off-axis object point are not condensed to a single point on the image plane but, instead, generate asymmetric blur that looks like a comet leaving traces. This is called coma aberration.

Figure 9-4 Coma Aberration and Spot Shape on the Image Plane



(3) Astigmatism
Even though a lens is compensated for spherical aberration and coma aberration, there are cases where an image of an off-axis object point is not focused to a single point but separated to a concentric line image and a radial line image. This is called astigmatism. When astigmatism is present, a point image blurs vertically and horizontally, before and after the focus position.

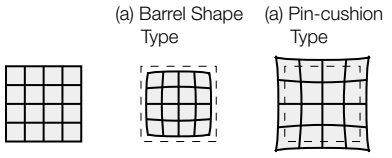
Figure 9-5 Astigmatism and Change in Spot Shape in Different Focus Positions



(4) Field Curvature
An image plane of an object on a plane perpendicular to an optical axis does not always become a plane perpendicular to the optical axis, but it generally becomes a curved plane. This symptom is called field curvature.
When field curvature is present, the image is more displaced as it becomes closer to the periphery of the visual field. Therefore, when the center of an image is brought into focus, blur occurs in the peripheral areas of the image. To bring the entire image, including the periphery, into clear focus, it is necessary to adequately compensate for this type of aberration.

(5) Distortion
When there is no similar relation between a planar shape on an object and a shape on the image plane, this is called distortion. When distortion is present, a square image appears in a shape of a barrel or pin-cushion as shown in Figure 9-6.

Figure 9-6 Distortion

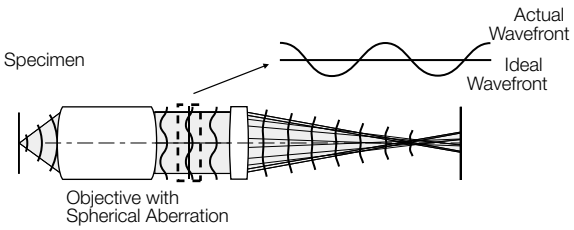


The microscope optical system contains some distortion. When distortion is present, it can bring erroneous results of shape measurements.
When a microscope is used for precision measurements, pay close attention to this aberration, for example, by providing it with an aberration compensation function.

(6) Chromatic Aberration
Glasses used for optical systems have different refractive indexes depending on the wavelength. This causes differences in focal length between wavelengths and generates displacement of image forming position. This phenomenon is called chromatic aberration, which is sometimes subdivided into axial displacement on the optical axis, called axial chromatic aberration (or lateral chromatic aberration) and displacement on the image plane, called chromatic aberration of magnitude.
Many special glass materials are used, e.g., for apochromats, to eliminate chromatic aberration in a wide range from violet light (g-rays with wavelength of 435 nm) to red light (c-rays with wavelength of 656 nm).

Based on the figure indicated for (1) spherical aberration, the behavior of the wavefront in an optical system that has an aberration is described below.

Figure 9-8 Illustration of Wavefront Aberration

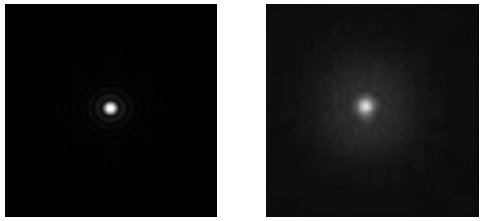


A difference (a degree of disagreement) between the ideal wavefront and the actual wavefront shown above is called wavefront aberration.

9.4 Strehl Ratio

When a point light source is observed with an aberration-free optical system and an aberrated optical system, the former concentrates the focal point to a point at the image formation position. In contrast, the latter fails to produce a focal point, instead causing a spread in the intensity distribution of the point image (this is known as point spread). The specific appearance of such a point image (i.e., point spread) is shown in Figure 9-9.

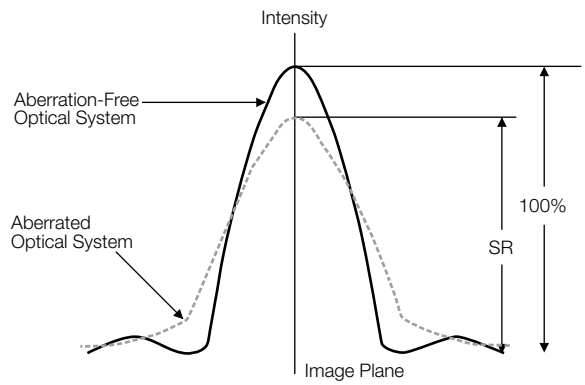
Figure 9-9 Appearance of Condensed Light in the Image Plane (point spread)



Optical Terminology

With the proportion of light concentrated in the image plane (intensity of light concentrated in the Airy disk) by an aberration-free optical system serving as 100%, the proportion of light concentrated by an aberrated optical system is known as the Strehl ratio (SR). When graphed, the Strehl ratio reveals peaks in intensity as shown in Figure 9-10. The higher the SR, the closer an optical system is to being aberration-free.

Figure 9-10 Strehl Ratio (SR)



A Strehl ratio of 80% is typically called the diffraction limit, and lenses with a lower ratio lack the performance required to serve as an objective. A ratio of over 95% means that the lens' performance in general observations is comparable to that of an aplanatic lens (which is corrected for spherical aberrations and coma).

Note: A laser interferometer is used to assess optical performance, so assessment is done at a single wavelength. Unless otherwise noted, Strehl ratio measurements are at the e-line (544 nm).