Optical Terminology

What is light to photography?

What is ‘light’?

Light is a physical phenomenon which involves creating vision by stimulating the optic nerves, and can be broadly defined as a type of electromagnetic wave.

Types of electromagnetic radiation vary according to wavelength. Starting from the shortest wavelengths, electromagnetic radiation can be classified into gamma rays, X rays, ultraviolet light rays, visible light rays, infrared light rays, far-infrared light rays, microwave radiation, ultra short wave radiation (VHF), short wave radiation, medium wave radiation (MF) and long wave radiation. In photography, the most utilised wavelengths are in the visible light region (400nm~700nm). Since light is a type of electromagnetic radiation, light can be thought of as a type of wave in the category of “light waves.” A light wave can be regarded as an electromagnetic wave in which an electric field and magnetic field vibrate at right angles to each other in a plane perpendicular to the direction of propagation. The two elements of a light wave which can actually be detected by the human eye are the wavelength and amplitude. Differences in wavelength are sensed as differences in colour (within the visible light range) and differences in amplitude are sensed as differences in brightness (light intensity). The third element which cannot be detected by the human eye is the direction of vibration within the plane perpendicular to the light wave’s direction of propagation (polarized light).

Figure-1 Approaching the human eye

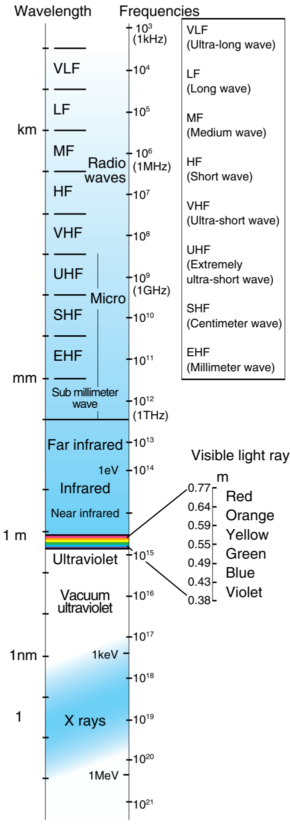
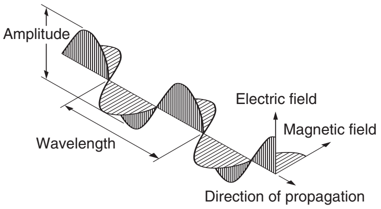


Figure-2 Approaching the human eye

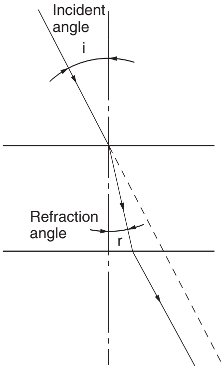


Basic light-related phenomena

Refraction

A phenomenon whereby the propagation direction of a ray of light changes when the light passes from one medium such as a vacuum or air into a different medium such as glass or water, or vice versa.

Figure-3 Light Refraction



Index of refraction

A numerical value indicating the degree of refraction of a medium, expressed by the formula n = sin i/sin r. “n” is a constant which is unrelated to the light ray’s angle of incidence and indicates the refractive index of the refracting medium with respect to the medium from which the light impinges.

For general optical glass, “n” usually indicates the index of refraction of the glass with respect to air.

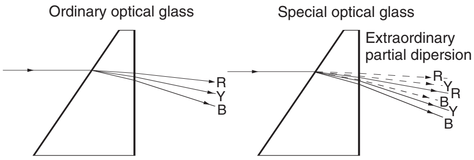
Dispersion

A phenomenon whereby the optical properties of a medium vary according to the wavelength of light passing through the medium. When light enters a lens or prism, the dispersion characteristics of the lens or prism cause the index of refraction to vary depending on the wavelength, thus dispersing the light. This is also sometimes referred to as colour dispersion.

Extraordinary partial dispersion

The human eye can sense monochromatic light wavelengths within the range of 400nm (purple) to 700nm (red). Within this range, the difference in index of refraction between two different wavelengths is called partial dispersion. Most ordinary optical materials have similar partial dispersion characteristics. However, partial dispersion characteristics differ for some glass materials, such as glass, which has larger partial dispersion at short wavelengths, FK glass which features a small index of refraction and low dispersion characteristics, fluorite, and glass which has larger partial dispersion at long wavelengths. These types of glass are classified as having extraordinary partial dispersion characteristics. Glass with this property is used in apochromatic lenses to compensate chromatic aberration.

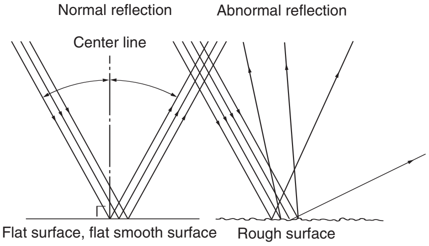
Figure-4 Light Dispersion by A Prism



Reflection

Reflection differs from refraction in that it is a phenomenon which causes a portion of the light striking the surface of glass or other medium to break off and propagate in an entirely new direction. The direction of propagation is the same regardless of wavelength. When light enters and leaves a lens which does not have an anti-reflection coating, approximately 5% of the light is reflected at the glass-air boundary. The amount of light reflected depends on the glass material’s index of refraction.→Coating (P.174)

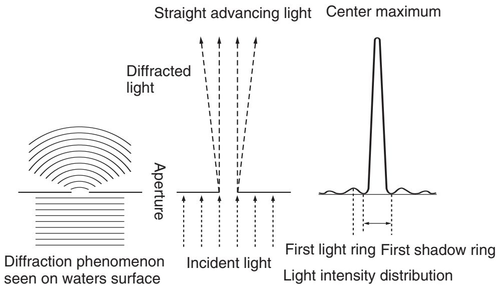
Figure-5 Light Reflection



Diffraction

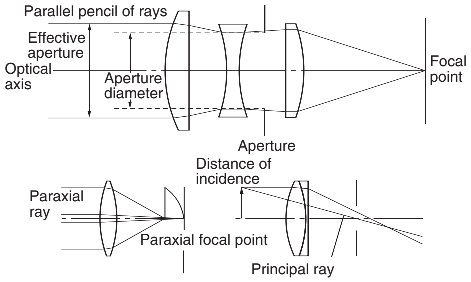
A phenomenon in which light waves pass around the edges of an object and enter the shadowed area of that object, caused because of the wavelike nature of light. Diffraction in a photographic lens is known for causing flare (diffraction flare) which occurs when light rays bend around the edges of the diaphragm. Although diffraction flare tends to appear when the diaphragm diameter is smaller than a certain size, it actually depends not only on the diameter of the diaphragm but also on various factors such as the wavelength of the light, the lens's focal length and the aperture ratio. Diffraction flare causes reductions in image contrast and resolution, resulting in a soft image. The laminated diffraction optical elements developed by Canon control the direction of the light by intentionally creating diffraction.

Figure-6 Light Diffraction



Optical terminology related to light passing through a lens

Figure-7 Optical Terminology Related To Light Passing Through A Lens



Optical axis

A straight line connecting the center points of the spherical surfaces on each side of a lens. In other words, the optical axis is a hypothetical center line connecting the center of curvature of each lens surface. In photographic lenses comprised of several lens elements, it is of utmost importance for the optical axis of each lens element to be perfectly aligned with the optical axes of all other lens elements. Particularly in zoom lenses, which are constructed of several lens groups that move in a complex manner, extremely precise lens barrel construction is necessary to maintain proper optical axis alignment.

Paraxial ray

A light ray which passes close to the optical axis and is inclined at a very small angle with respect to the optical axis. The point at which paraxial rays converge is called the paraxial focal point. Since the image formed by a monochromatic paraxial ray is in principle free of aberrations, the paraxial ray is an important factor in understanding the basic operation of lens systems.

Principal ray

A light ray which enters the lens at an angle at a point other than the optical axis point and passes through the center of the diaphragm opening. Principal light rays are the fundamental light rays used for image exposure at all diaphragm openings from maximum aperture to minimum aperture.

Parallel pencil of rays

A group of light rays traveling parallel to the optical axis from an infinitely far point. When these rays pass through a lens, they converge in the shape of a cone to form a point image within the focal plane.

Ray tracing

Use of geometrical optics to calculate the condition of various light rays passing through a lens. Calculations are performed using powerful computers.

Aperture/effective aperture

The aperture of a lens is related to the diameter of the group of light rays passing through the lens and determines the brightness of the subject image formed on the focal plane. The optical aperture (also called the effective aperture) differs from the real aperture of the lens in that it depends on the diameter of the group of light rays passing through the lens rather than the actual lens diameter. When a parallel pencil of rays enters a lens and a group of these rays passes through the diaphragm opening, the diameter of this group of light rays when it enters the front lens surface is the effective aperture of the lens.

Stop/diaphragm/aperture

The opening which adjusts the diameter of the group of light rays passing through the lens. In interchangeable lenses used with single lens reflex cameras, this mechanism is usually constructed as an iris diaphragm consisting of several blades which can be moved to continuously vary the opening diameter. With conventional SLR camera lenses, the aperture is adjusted by turning an aperture ring on the lens barrel. With modern camera lenses, however, aperture adjustment is commonly controlled by operating an electronic dial on the camera body.

Circular aperture diaphragm

With normal aperture diaphragms, closing the aperture causes its shape to become polygonal. A circular aperture diaphragm, on the other hand, optimises the shape of the blades to achieve a nearly perfect circle even when considerably stopped down from the maximum aperture. Photography with a lens that is equipped with a circular aperture diaphragm achieves a beautiful blur effect for the background, because the point source is circular.

Automatic diaphragm

The general diaphragm operation system used in SLR cameras, referring to a type of diaphragm mechanism which remains fully open during focusing and composition to provide a bright viewfinder image, but automatically closes down to the aperture setting necessary for correct exposure when the shutter button is pressed and automatically opens up again when the exposure is completed. Although conventional lenses use mechanical linkages for controlling this automatic diaphragm operation, EF lenses use electronic signals for more precise control. You can observe this instantaneous aperture stop-down operation by looking into the front of the lens when the shutter is released.

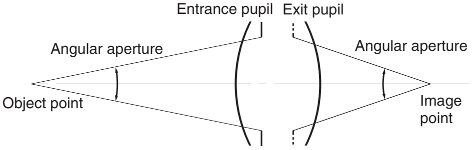
Distance of incidence

Distance from the optical axis of a parallel ray entering a lens.

Entrance pupil/exit pupil

The lens image on the object side of the diaphragm, i.e. the apparent aperture seen when looking from the front of the lens, is called the entrance pupil and is equivalent in meaning to the lens' effective aperture. The apparent aperture seen when looking

Figure-8 Pupils and Angular Aperture



from the rear of the lens (the lens image on the image side of the diaphragm), is called the exit pupil. Of the light rays from a certain subject point, the effective light rays which actually form the image create a cone of light rays with the subject point being the point of the cone and the entrance pupil being the base of the cone. At the other end of the lens, the light rays emerge in a cone shape with the exit pupil forming the base of the cone and the point of the cone falling within the image plane. The entrance and exit pupils have the same shape as the actual diaphragm and their size is directly proportional to that of the diaphragm, so even if the construction of the lens system is not known, it is possible to graphically illustrate the effective light rays which actually form the image as long as the positions and sizes of the entrance and exit pupils are known. Thus, knowledge of the entrance and exit pupils is indispensable when considering performance factors such as the total amount of light entering the lens, the manner in which the image blurs and aberrations.

Angular aperture

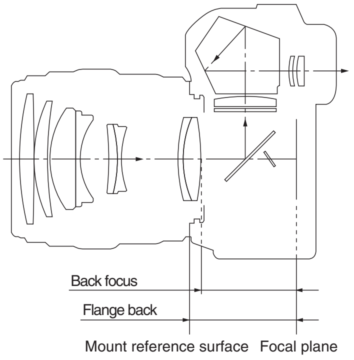
The angle between the subject point on the optical axis and the diameter of the entrance pupil, or the angle between the image point on the optical axis and the diameter of the exit pupil.

Flange back and back focus

Flange back

Distance from the camera's lens mount reference surface to the focal plane (film plane). In the EOS system, flange back is set at 44.00 mm on all cameras. Flange back is also referred to as flange-focal distance.

Figure-9 Flange Back and Back Focus



Back focus

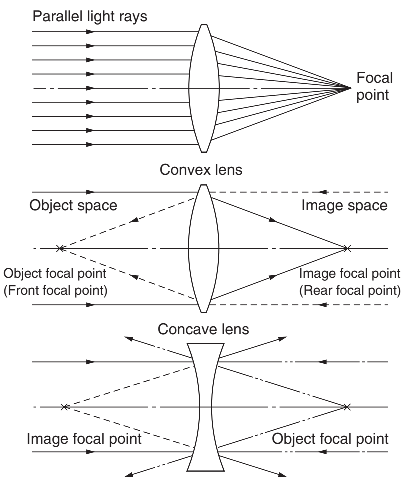
With a lens focused to infinity, the distance along the optical axis from the apex of the rearmost glass surface to the focal plane is called back focus. Wide-angle lenses with a short back focus cannot be used on SLR cameras that use a mirror that swings up before exposure because the lens will obstruct the mirror movement. Wide-angle lenses for SLR cameras generally employ a retrofocus design which allows a long back focus. The compact size of the quick-return mirror on the EF-S lens compatible digital SLR cameras makes it possible to design lenses like the dedicated EF-S 60mm f/2.8 Macro USM, EF-S 10-22mm f/3.5-4.5 USM, EF-S 17-55mm f/2.8 IS USM and EF-S 18-55mm f/3.5-5.6 II USM lenses with a shorter back focus than in other EF lenses.

Focal point and focal length

Focal point, focus

When light rays enter a convex lens parallel to the optical axis, an ideal lens will converge all the light rays to a single point from which the rays again fan out in a cone shape. This point at which all rays converge is called the focal point. A familiar example of this is when a magnifying glass is used to focus the rays of the sun to a small circle on a piece of paper or other surface; the point at which the circle is smallest is the focal point. In optical terminology, a focal point is further classified as being the rear or image-side focal point if it is the point at which light rays from the subject converge on the film plane side of the lens. It is the front or object-side focal point if it is the point at which light rays entering the lens parallel to the optical axis from the focal plane side converge on the object side of the lens.

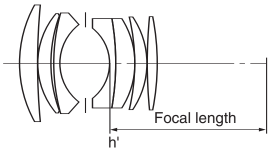
Figure-10 Focal Point (single lens element)



Focal length

When parallel light rays enter the lens parallel to the optical axis, the distance along the optical axis from the lens' second principal point (rear nodal point) to the focal point is called the focal length. In simpler terms, the focal length of a lens is the distance along the optical axis from the lens' second principal point to the focal plane when the lens is focused at infinity.

Figure-11 Focal Length of Actual Photographic Lens

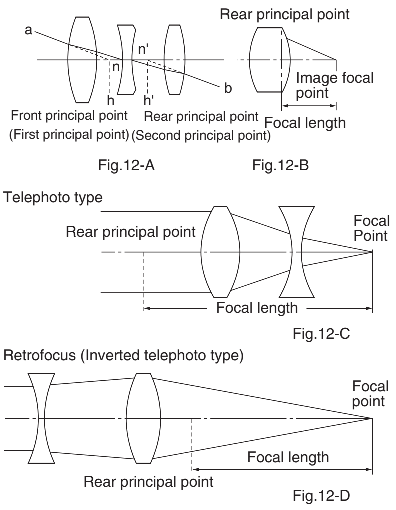


Principal point

The focal length of a thin, double-convex, single-element lens is the distance along the optical axis from the center of the lens to its focal point. This center point of the lens is called the principal point. However, since actual photographic lenses consist of combinations of several convex and concave lens elements, it is not visually apparent where the center of the lens might be.

The principal point of a multi-element lens is therefore defined as the point on the optical axis at a distance equal to the focal length measured back toward the lens from the focal point. The principal point measured from the front focal point is called the front principal point, and the principal point measured from the rear focal point is called the rear principal

Figure-12 Principal point



point. The distance between these two principal points is called the principal point interval.

Front principal point/rear principal point

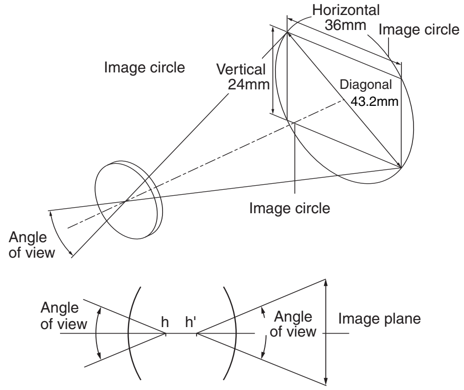
Light entering a lens from point a in Figure-12-A refracts, passes through n and n' and arrives at b. When this occurs, similar angles are generated between a-n and n'-b with respect to the optical axis, and points h and h' can be defined as where these angles intersect the optical axis. These points, h and h', are principal points indicating the lens reference positions with respect to the subject and image. h is called the front principal point (or first principal point) and h' is called the rear principal point (or second principal point). In general photographic lenses, the distance from h' to the focal point (focal plane) is the focal length. Depending on the lens type, the front-rear relationship of the principal points may be reversed, or h' may fall outside of the lens assembly altogether, but in any case the distance from the rear principal point h' to the focal point is equal to the focal length.

*With telephoto type lenses, the rear principal point h' is actually positioned in front of the frontmost lens element, and with retrofocus type lenses h' is positioned to the rear of the rearmost lens element.

Image circle

The portion of the circular image formed by a lens that is sharp. Interchangeable lenses for 35mm format cameras must have an image circle at least as large as the diagonal of the 24 x 36mm image area. EF lenses therefore generally have an image circle of about 43.2mm diameter. TS-E lenses, however, are designed with a larger image circle of 58.6mm to cover the lens's tilt and shift movements. EF-S lenses feature a smaller image circle than other EF lenses, to match the diagonal of the APS-C sized image sensor of EF-S compatible digital SLR cameras.

Figure-13 Angle of view and image circle



Angle of view

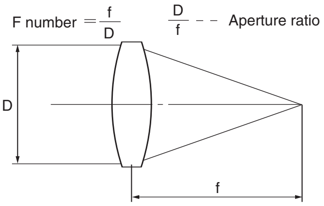
The area of a scene, expressed as an angle, which can be reproduced by the lens as a sharp image. The nominal diagonal angle of view is defined as the angle formed by imaginary lines connecting the lens' second principal point with both ends of the image diagonal (43.2mm). Lens data for EF lenses generally includes the horizontal (36mm) angle of view and vertical (24mm) angle of view in addition to the diagonal angle of view.

Terms related to lens brightness

Aperture ratio

A value used to express image brightness, calculated by dividing the lens' effective aperture (D) by its focal length (f). Since the value calculated from D/f is almost always a small decimal value less than I and therefore difficult to use practically, it is common to express the aperture ratio on the lens barrel as the ratio of the effective aperture to the focal length, with the effective aperture set equal to 1. (For example, the EF 85mm f/1.2L II USM lens barrel is imprinted with 1 : 1.2, indicating that the focal length is 1.2 times the effective aperture when the effective aperture is equal to 1.) The brightness of an image produced by a lens is proportional to the square of the aperture ratio. In general, lens brightness is expressed as an F number, which is the inverse of the aperture ratio (f/D). F number

Figure-14 Lens Brightness



F number

Since the aperture ratio (D/f) is almost always a small decimal value less than one and therefore difficult to use practically, lens brightness is often expressed for convenience' sake as the inverse of the aperture ratio (f/D), which is called the F number. Accordingly, image brightness is inversely proportional to the square of the F number, meaning that the image becomes darker as the F number increases. F number values are expressed as a geometrical series starting at 1 with a common ratio of $\sqrt{2}$, as follows: 1.0, 1.4, 2, 2.8, 4, 5.6, 8, 16, 22, 32, etc. (However, there are many cases where only the maximum aperture value deviates from this series.) The numbers in this series, which may at first seem difficult to become familiar with, merely indicate values which are close to the actual FD values based on the diameter (D) of each successive diaphragm setting which decreases the amount of light passing through the lens by half. Thus, changing the F number from 1.4 to 2 halves the image brightness, while going the other direction from 2 to 1.4 doubles the image brightness. (A change of this magnitude is generally referred to as "1 stop".) With recent cameras employing electronic displays, smaller divisions of 1/2 stop or even 1/3 stop are used.

Numerical aperture (NA)

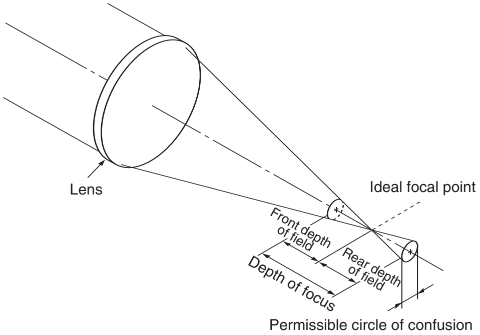
A value used to express the brightness or resolution of a lens' optical system. The numerical aperture, usually indicated as NA, is a numerical value calculated from the formula $n\sin\theta$, where 2θ is the angle (angular aperture) at which an object point on the optical axis enters the entrance pupil and n is the index of refraction of the medium in which the object exists. Although not often used with photographic lenses, the NA value is commonly imprinted on the objective lenses of microscopes, where it is used more as an indication of resolution than of brightness. A useful relationship to know is that the NA value is equal to half the inverse of the F number. For example, F 1.0 = NA 0.5, F 1.4 = NA 0.357, F2 = NA 0.25, and so on.

Focus and depth of field

Focus, focal point

The focal point is the point where parallel light rays from an infinitely far subject converge after passing through a lens. The plane perpendicular to the optical axis which contains this point is called the focal plane. In this plane, which is where the film or the image sensor is positioned in a camera, the subject is sharp and said to be "in focus." With general photographic lenses consisting of several lens elements, the focus can be adjusted so that light rays from subjects closer than "infinity" converge at a point in the focal plane.

Figure-15 Relationship Between the Ideal Focal Point and the Permissible Circle of Confusion and Depth of Field



Circle of confusion

Since all lenses contain a certain amount of spherical aberration and astigmatism, they cannot perfectly converge rays from a subject point to form a true image point (i.e., an infinitely small dot with zero area). In other words, images are formed from a composite of dots (not points) having a certain area, or size. Since the image becomes less sharp as the size of these dots increases, the dots are called "circles of confusion." Thus, one way of indicating the quality of a lens is by the smallest dot it can form, or its "minimum circle of confusion." The maximum allowable dot size in an image is called the "permissible circle of confusion."

Permissible circle of confusion

The largest circle of confusion which still appears as a "point" in the image. Image sharpness as sensed by the human eye is closely related to the sharpness of the actual image and the "resolution" of human eyesight. In photography, image sharpness is also dependent on the degree of image enlargement or projection distance and the distance from which the image is viewed. In other words, in practical work it is possible to determine certain "allowances" for producing images which, although actually blurred to a certain degree, still appear sharp to the observer. For 35mm single lens reflex cameras, the permissible circle of confusion is about 1/1000~1/1500 the length of the film diagonal, assuming the image is enlarged to a 5"×7" (12 cm × 16.5 cm) print and viewed from a distance of 25~30 cm/0.8~1 ft. EF lenses are designed to produce a minimum circle of confusion of 0.035 mm, a value on which calculations for items such as depth of field are based.

Depth of field

The area in front of and behind a focused subject in which the photographed image appears sharp. In other words, the depth of sharpness to the front and rear of the subject where image blur in the focal plane falls within the limits of the permissible circle of confusion. Depth of field varies according to the lens' focal length, aperture value and shooting distance, so if these values are known, a rough estimate of the depth of field can be calculated using the following formulas:

Front depth of field $= d{\cdot}F{\cdot}a^2/(f^2 + d{\cdot}F{\cdot}a)$

Rear depth of field $= d{\cdot}F{\cdot}a^2/(f^2 - d{\cdot}F{\cdot}a)$

f: focal length F: F number d: minimum circle of confusion diameter

a: subject distance (distance from the first principal point to subject)

$$\text{Near point limiting distance} = \frac{\text{hyperfocal distance} \times \text{shooting distance}}{\text{hyperfocal distance} + \text{shooting distance}}$$

$$\text{Far point limiting distance} = \frac{\text{hyperfocal distance} \times \text{shooting distance}}{\text{hyperfocal distance} - \text{shooting distance}}$$

(Shooting distance: Distance from focal plane to subject)

If the hyperfocal distance is known, the following formulas can also be used:

In general photography, depth of field is characterised by the following attributes:

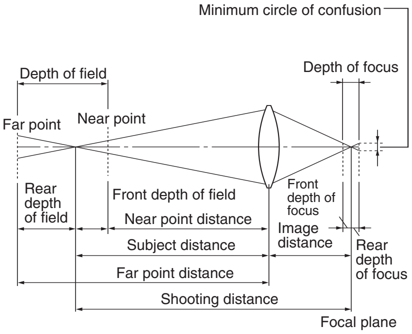
① Depth of field is deep at short focal lengths, shallow at long focal lengths.

② Depth of field is deep at small apertures, shallow at large apertures.

③ Depth of field is deep at far shooting distances, shallow at close shooting distances.

④ Front depth of field is shallower than rear depth of field.

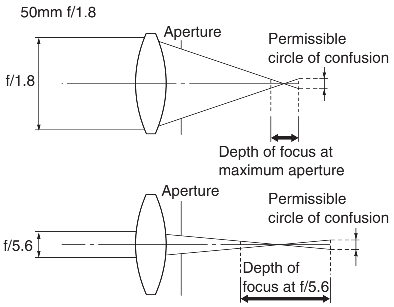
Figure-16 Depth of Field and Depth of Focus



Depth of focus

The area in front of and behind the focal plane in which the image can be photographed as a sharp image. Depth of focus is the same on both sides of the image plane (focal plane) and can be determined by multiplying the minimum circle of confusion by the F number, regardless of the lens focal length. With modern autofocus SLR cameras, focusing is performed by detecting the state of focus in the image plane (focal plane) using a sensor which is both optically equivalent (1:1 magnification) and positioned out of the focal plane, and automatically controlling the lens to bring the subject image within the depth of focus area.

Figure-17 Relationship Between Depth of Focus and Aperture



Hyperfocal distance

Using the depth of field principle, as a lens is gradually focused to farther subject distances, a point will eventually be reached where the far limit of the rear depth of field will be equivalent to "infinity." The shooting distance at this point, i,e., the closest shooting distance at which "infinity" falls within the depth of field, is called the hyperfocal distance. The hyperfocal distance can be determined as follows:

$$\text{Hyperfocal distance} = \frac{f^2}{d{\bullet}F\ \text{number}}$$

f: focal length F: F number

d: minimum circle of confusion diameter

Thus, by presetting the lens to the hyperfocal distance, the depth of field will extend from a distance equal to half the hyperfocal distance to infinity. This method is useful for presetting a large depth of field and taking snapshots without having to worry about adjusting the lens focus, especially when using a wide-angle lens. (For example, when the EF 20mm f/2.8 USM is set to f/16 and the shooting distance is set to the hyperfocal distance of approximately 0.7m/2.3ft, all subjects within a range of approximately 0.4m/1.3ft from the camera to infinity will be in focus.)

Photo-1 Hyperfocal Length Set Condtion

Lens aberration

Aberration

The image formed by an ideal photographic lens would have the following characteristics:

① A point would be formed as a point.

② A plane (such as a wall) perpendicular to the optical axis would be formed as a plane.

③ The image formed by the lens would have the same shape as the subject.

Also, from the standpoint of image expression, a lens should exhibit true colour reproduction. If only light rays entering the lens close to the optical axis are used and the light is monochromatic (one specific wavelength), it is possible to realise virtually ideal lens performance. With real photographic lenses, however, where a large aperture is used to obtain sufficient brightness and the lens must converge light not only from near the optical axis but from all areas of the image, it is extremely difficult to satisfy the above-mentioned ideal conditions due to the existence of the following obstructive factors:

● Since most lenses are constructed solely of lens elements with spherical surfaces, light rays from a single subject point are not formed in the image as a perfect point. (A problem unavoidable with spherical surfaces.)

● The focal point position differs for different types (i.e., different wavelengths) of light.

● There are many requirements related to changes in angle of view (especially with wide-angle, zoom and telephoto lenses).

The general term used to describe the difference between an ideal image and the actual image affected by the above factors is "aberration." Thus, to design a high-performance lens, aberration must be extremely small, with the ultimate objective being to obtain an image as close as possible to the ideal image. Aberration can be broadly divided into chromatic aberrations, and monochromatic aberrations → Chromatic aberration → Five aberrations of Seidel

Table-1 Lens Aberrations

Aberrations seen in the continuous spectrum
- ■Chromatic aberrations
  - ●Axial chromatic aberration (longitudinal chromatic aberration)
  - ●Transverse chromatic aberration (lateral chromatic aberration)

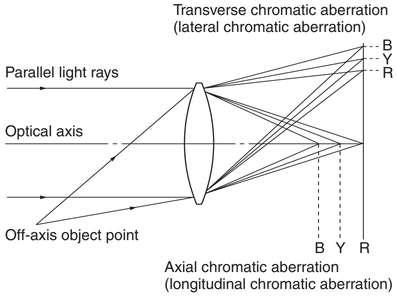
Aberrations seen at specific wavelengths
- ■Five aberrations of Seidel
  - ① Spherical aberration
  - ② Chromatic aberration
  - ③ Astigmatism
  - ④ Curvature of field
  - ⑤ Distortion

Chromatic aberration

When white light (light containing many colours uniformly mixed so that the eye does not sense any particular colour and thus perceives the light as white) such as sunlight is passed through a prism, a rainbow spectrum can be observed. This phenomenon occurs because the prism's index of refraction (and rate of dispersion) varies depending on the wavelength (short wavelengths are more strongly refracted than long wavelengths). While most visible in a prism, this phenomenon also occurs in photographic lenses, and since it occurs at different wavelengths is called chromatic aberration. There are two types of chromatic aberration: "axial chromatic aberration," where the focal point position on the optical axis varies according to the wavelength, and "chromatic difference of magnification," where the image magnification in peripheral areas varies according to the wavelength. In actual photographs, axial chromatic aberration appears as colour blur or flare, and chromatic difference of magnification appears as colour fringing (where edges show colour along their borders). Chromatic aberration in a photographic lens is corrected by combining different types of optical glass having different refraction and dispersion characteristics. Since the effect of chromatic aberration increases at longer focal lengths, precise chromatic aberration correction is particularly important in super-telephoto lenses for good image sharpness. Although there is a limit to the degree of correction possible with optical glass, significant performance improvements can be achieved using man-made crystal such as fluorite or UD glass. Axial chromatic aberration is also sometimes referred to as "longitudinal chromatic aberration" (since it occurs longitudinally with respect to the optical axis), and chromatic difference of magnification can be referred to as "lateral chromatic aberration" (since it occurs laterally with respect to the optical axis).

Figure-18 Chromatic Aberration

●This phenomenon occurs because the prism's index of refraction varies depending on the wavelength (colour).



Note: While chromatic aberration is most noticeable when using colour film, it affects black-and-white images as well, appearing as a reduction in sharpness.

Achromat

A lens which corrects chromatic aberration for two wavelengths of light. When referring to a photographic lens, the two corrected wavelengths are in the blue-violet range and yellow range.

Apochromat

A lens which corrects chromatic aberration for three wavelengths of light, with aberration reduced to a large degree particularly in the secondary spectrum. EF super-telephoto lenses are examples of apochromatic lenses.

Five aberrations of Seidel

In 1856, a German named Seidel determined through analysis the existence of five lens aberrations which occur with monochromatic (single wavelength) light. These aberrations, described below, are called the five aberrations of Seidel.

① Spherical aberration

This aberration exists to some degree in all lenses constructed entirely of spherical elements. Spherical aberration causes parallel light rays passing through the edge of a lens to converge at a focal point closer to the lens than light rays passing through the center of the lens. (The amount of focal point shift along the optical axis is called longitudinal spherical aberration.) The degree of spherical aberration tends to be larger in large-aperture lenses. A point image affected by spherical aberration is sharply formed by light rays near the optical axis but is affected by flare from the peripheral light rays (this flare is also called halo, and its radius is called lateral spherical aberration). As a result, spherical

Figure-19 Spherical Aberration

●This is the phenomenon where the focus is not concentrated on one point on the light ray but rather is offset to the front or back.

Occurrence of a halo——The image becomes flare.

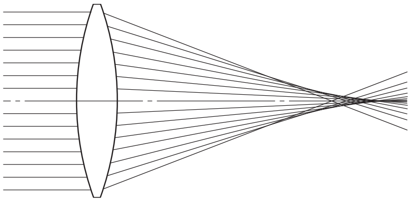
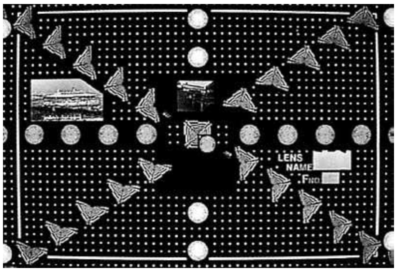
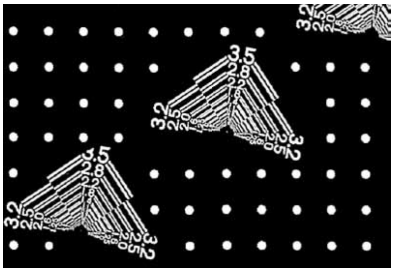


Photo-2 The photographs are magnifications of the subject and surrounding area from part of a test chart photographed with a 24mm x 36mm film frame and printed on quarter size paper.

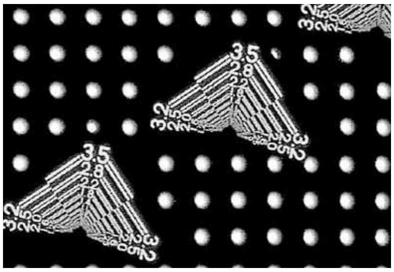


Almost ideal image formation

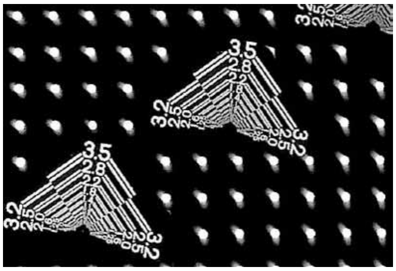


Peripheral ▭ part magnified

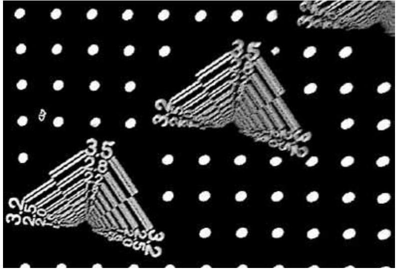
① Example of spherical aberration



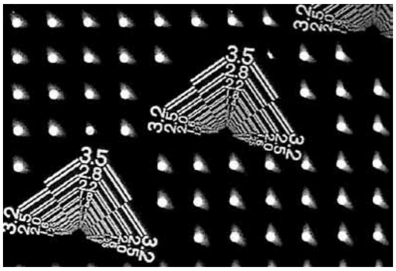
②-1 Example of inward coma



③ Example of astigmatism



②-2 Example of outward coma



aberration affects the entire image area from the center to the edges, and produces a soft, low-contrast image which looks as if covered with a thin veil. Correction of spherical aberration in spherical lenses is very difficult. Although commonly carried out by combining two lenses –– one convex and one concave –– based on light rays with a certain height of incidence (distance from the optical axis), there is a limit to the degree of correction possible using spherical lenses, so some aberration always remains. This remaining aberration can be largely eliminated by stopping down the diaphragm to cut the amount of peripheral light. With large aperture lenses at full aperture, the only effective way to thoroughly compensate spherical aberration is to use an aspherical lens element. → Aspherical lens

② Coma, comatic aberration

Coma, or comatic aberration, is a phenomenon visible in the periphery of an image produced by a lens which has been corrected for spherical aberration, and causes light rays entering the edge of the lens at an angle to converge in the form of a comet instead of the desired point, hence the name. The comet shape is oriented radially with the tail pointing either toward or away from the center of the image. The resulting blur near the edges of the image is called comatic flare. Coma, which can occur even in lenses which correctly reproduce a point as a point on the optical axis, is caused by a difference in refraction between light rays from an off-axis point passing through the edge of the lens and the principal light ray from the same point passing through the lens center. Coma increases as the angle of the principal ray increases, and causes a decrease in contrast near the edges of the image. A certain degree of improvement is possible by stopping down the lens. Coma can also cause blurred areas of an image to flare, resulting in an unpleasing effect. The elimination of both spherical aberration and coma for a subject at a certain shooting distance is called aplanatism, and a lens corrected as such is called an aplanat.

Figure-20 Comatic Aberration

●This is the phenomenon where the diagonal light rays do not focus on one point on the image surface.

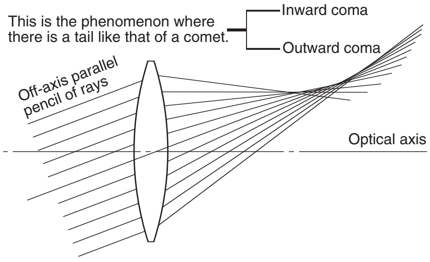


Photo-3 Axial chromatic aberration

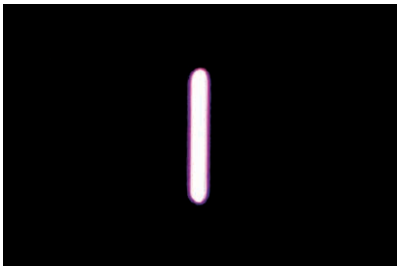
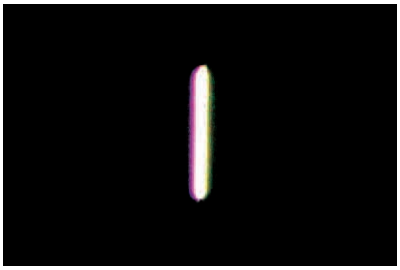


Photo-4 Transverse chromatic aberration

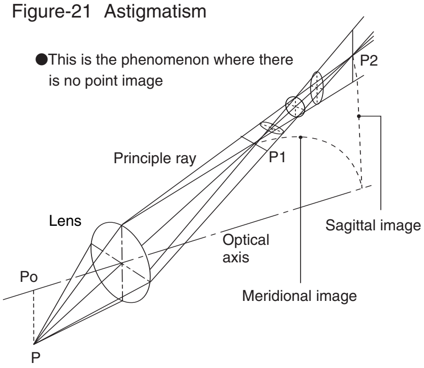


③ Astigmatism

With a lens corrected for spherical and comatic aberration, a subject point on the optical axis will be correctly reproduced as a point in the image, but an off-axis subject point will not appear as a point in the image, but rather as an ellipse or line. This type of aberration is called astigmatism, It is possible to observe this phenomenon near the edges of the image by slightly shifting the lens focus to a position

Figure-21 Astigmatism

●This is the phenomenon where there is no point image



where the subject point is sharply imaged as a line oriented in a direction radiating from the image center, and again to another position.

④ Curvature of Field

This is the phenomenon where, when focusing on a flat surface, the image does not become flat, but where the image is formed in a bowed shape to the inside of the bowl. Therefore, when focusing on the center of the frame, the circumference is blurred, and conversely, when focusing on the circumference, the center is blurred. This image bending is mainly changed using the astigmatism correction method, which creates an image between a sagittal image and a meridional image, so the more the astigmatism is corrected, the smaller the image becomes. Because there is almost no corrective effect from stopping down the lens, various efforts are made during designing, such as changing the shape of the single lenses of the lens configuration and selecting the aperture position, but one of the requirements for correcting astigmatism and image bending at the same time is Petzval's condition (1843). This condition is that the inverse of the product of the index of refraction for each of the single lenses of the lens configuration and the focal distance added with the number of single lenses used in the lens configuration must produce a sum of 0. This sum is called Petzval's sum.

Figure-22 Curvature of field

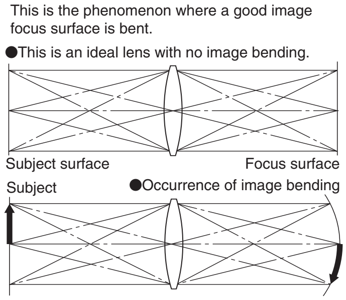
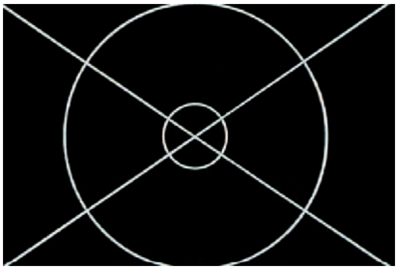
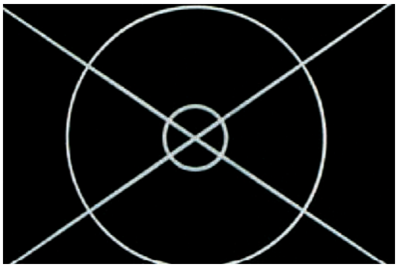


Photo-5 Example of curvature of field



Focusing on center of screen causes corners to go out of focus.

Photo-6 Example of curvature of field



Focusing on corners of screen causes center to go out of focus.

⑤ Distortion

One of the conditions for an ideal lens is that "the image of the subject and the image formed by the lens are similar," and the deviation from this ideal where the straight lines are bent is called distortion. The extended shape in the diagonal view angle direction (+) is called pincushion distortion, and, conversely, the contracted shape (–) is called barrel distortion. With an ultra wide-angle lens, rarely do both of these distortions exist together. Although this seldom occurs in lenses where the lens combination configuration is at the aperture boundary, it occurs easily in configuration lenses. Typical zoom lenses tend to exhibit barrel distortion at the shortest focal lengths and pincushion distortion at the longest focal lengths (the distortion characteristics change slightly during zooming), but in zoom lenses that use an aspherical lens, the aspherical lens is effective at removing distortion, so the correction is good. This difference is caused by the difference in refraction of the principal rays passing through the center of the lens, so it cannot be improved no matter how much the aperture is stopped down.

Figure-23 Distortion

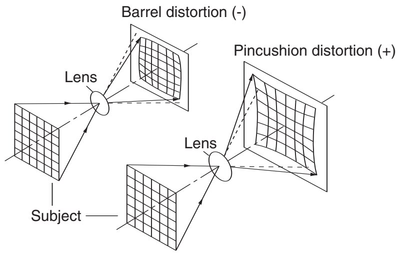
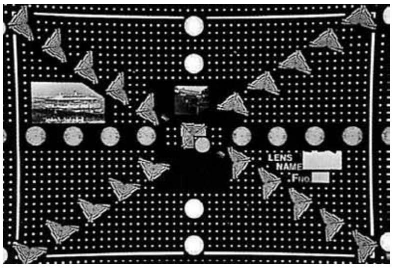
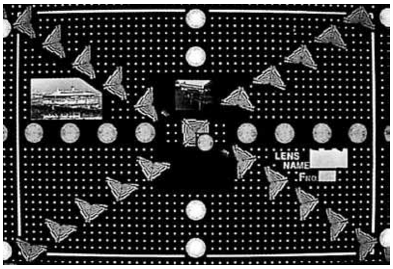


Photo-7 Example of distortion



+•Pincushion distortion

Photo-8 Example of distortion



-•Barrel distortion

Meridional

A plane that includes a principal ray that tries to capture a point outside the optical axis and the optical axis is called a meridional plane. The position linked to the focal point by the light ray entering through a lens of this shape is called the meridional image plane. This is the image plane where the image of concentric circles in the frame are at the best. If the spherical surface of the lens is compared to a portion of the earth's curvature and if the optical axis is compared to the earth's axis, the meridional plane would be where the earth's meridian is, which is why this name is used. The curve that expresses the characteristics of this image plane using a MTF characteristics graph, etc., is often abbreviated as "M."

Sagittal

The plane that is perpendicular to the meridional plane is called the sagittal plane, and this is the image plane where the radial image is at its best. The word comes from the Greek word for arrow. The name comes from the shape of the focal point, which spreads radially. The position linked to the focal point of a light ray that passes through a sagittal plane shape and into a lens is called the sagittal image plane, and when the characteristics of this image plane are expressed using a MTF characteristics graph, etc., it is often abbreviated using the initial "S."

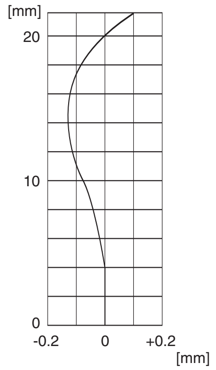
How to Read Distortion Graphs

A simple way of reading the aberration graphs that accompany test report articles in camera magazines.

● Spherical Distortion Characteristics Graph (Graph1)

The vertical axis of the graph shows the height of entry above the axis entering the lens system (distance above the diagonal from the center of the frame), and the horizontal axis shows the image point offset captured by the film surface shape. The unit is mm. The horizontal axis symbols are "–" (minus), which shows the subject's side direction, and "+" (plus), which shows the film's side direction. The ideal lens characteristic is for the horizontal axis zero point to form a straight line with the entry height. The difference between this ideal and the actual lens is shown as a curve. Spherical distortion correction is generally said to be good if there is a core in the image and the focal point moves little when the lens is stopped down, in other words, there is slightly insufficient correction in the middle area while at the maximum entry height there is perfect correction where it returns nearly to zero.

Figure-24 Spherical Distortion Characteristics Graph (Graph 1)



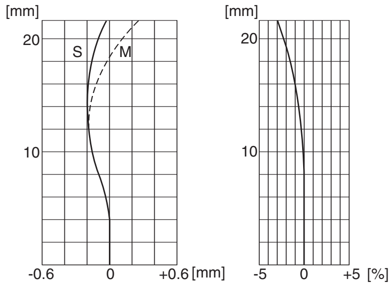
● Astigmatism curve (Graph 2)

The graph's vertical axis is the axial height of incidence (distance from the image center) of the ray entering the lens system, and the horizontal axis is the amount of shift of the image point formed in the focal plane. Units and signs are the same as in the spherical aberration curve. The curve for an ideal lens would be a straight line at the horizontal axis' zero point with respect to the height of incidence. The difference between the ideal lens and actual lens is indicated by two curved lines in the S direction (sagittal/radial direction) and M direction (meridional/concentric circle direction). If the difference between S and M (astigmatic difference) is large, a point will not be formed as a point and the image will smear. Moreover, the blur image in front of and behind the image formation plane will be unnatural.

● Distortion curve (Graph 3)

The graph's vertical axis is the axial height of incidence (distance from the image center; unit: mm) of the ray entering the lens system, and the horizontal axis is percent (%) distortion. The curve indicates the difference between the ideal image and the actual image formed at the focal plane. A minus sign indicates negative, or barrel, distortion where the length of the diagonal of the actual image is shorter than the diagonal of the ideal image. A plus sign indicates positive, or pincushion, distortion. An ideal lens would exhibit ±0% distortion at any image height. Distortion curves for zoom lenses generally show barrel distortion at wide-angle positions and pincushion distortion at telephoto positions.

Figure-25 Astigmatism Curve (Graph2) Distortion Curve (Graph3)



How to minimise the effects of aberrations

Modern lenses are designed using large-scale computers to perform mind-boggling calculations and high-level simulations to minimise all types of aberration and achieve superior image formation performance. Even with this technology, however, it is impossible to completely remove all aberrations, meaning that all lenses on the market still have at least a small amount of aberration remaining. This aberration is called residual aberration. The type of residual aberration in a lens generally determines the lens' imaging characteristics such as its sharpness and blur effect. Because of this, modern lenses are often designed with consideration given to achieving a pleasing blur effect (image characteristics outside the image formation plane) by using computer simulation techniques to analyze lens performance at the design stage. As mentioned in the various aberration descriptions, the effects of some aberrations can be minimised by stopping down the lens, while others cannot. The relationships between aperture and aberrations are shown in Table 2.

Lens performance evaluation

Resolving power/resolution

The resolution of a lens indicates the capacity of reproduction of a subject point of the lens. The resolution of the final photograph depends on three factors: the resolution of the lens, the resolution of the film or image sensor, and the resolution of the printer or printing paper. Resolution is evaluated by photographing, at a specified

Figure-26 Resolution Measurement Charts

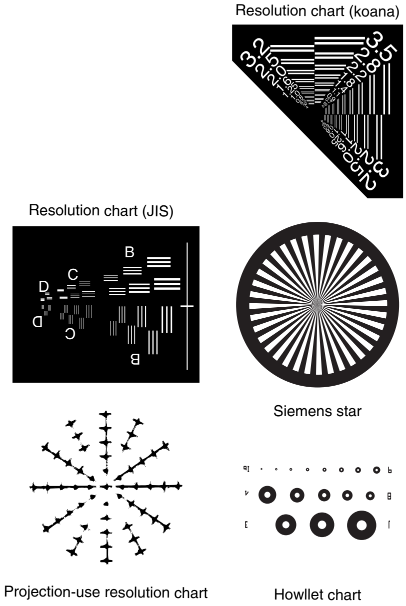

Resolution chart (koana)
Resolution chart (JIS)
Siemens star
Projection-use resolution chart
Howlett chart

Table-2 Relationship between aperture and aberration

Cause of drop in image quality	Areas affected on the screen	Improvement by smaller aperture
Axial colour aberration	Center and edges	Slight effect
Magnification colour aberration	Edges	No effect
Spherical aberration	Center and edges	Effect present
Comatic aberration	Edges	Effect present
Astigmatism	Edges	Slight effect
Curvature of field	Edges	Slight effect
Distortion	Edges	No effect
Ghosting/flaring	Center and edges	No effect
Drop in peripheral illumination	Edges	Effect present

magnification, a chart containing groups of black and white stripes that gradually decrease in narrowness, then using a microscope to observe the negative image at a magnification of 50x.

It is common to hear resolution expressed as a numerical value such as 50 lines or 100 lines. This value indicates the number of lines per millimeter of the smallest black and white line pattern which can be clearly recorded on the film. To test the resolution of a lens alone, a method is used in which a fine resolution chart is positioned in the location corresponding to the focal plane and projected through the test lens onto a screen. The numerical value used for expressing resolving power is only an indication of the degree of resolution possible, and does not indicate resolution clarity or contrast.

Contrast

The degree of distinction between areas of different brightness levels in a photograph, i.e., the difference in brightness between light and dark areas. For example, when the reproduction ratio between white and black is clear, contrast is said to be high, and when unclear, contrast is said to be low. In general, lenses producing high quality images have both high resolution and high contrast.

Figure-27 Contrast Concept Diagram

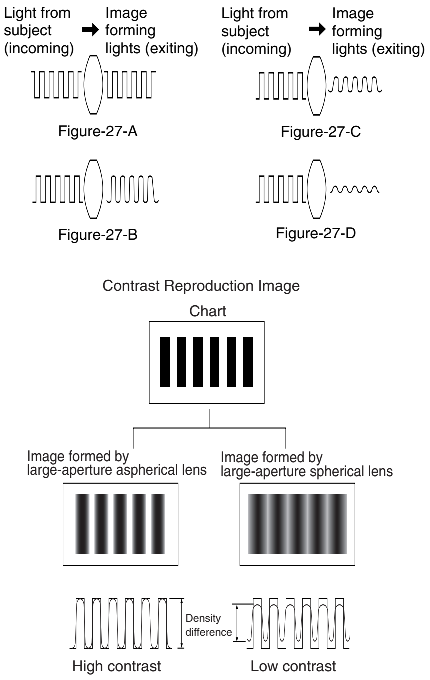


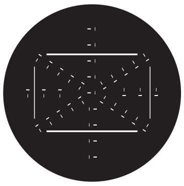
Figure-27-A

Figure-27-C

Figure-27-B

Figure-27-D

Figure-27-E MTF Measurement-Use Slit Chart



MTF (modulation transfer function)

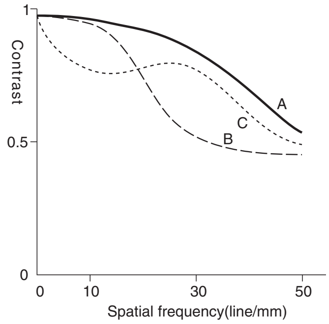
Modulation transfer function is a lens performance evaluation method used to determine the contrast reproduction ratio, or sharpness, of a lens. When evaluating the electrical characteristics of audio equipment, one important measure of performance is frequency response. In this case, where the source sound is recorded through a microphone and then played back through speakers, frequency response indicates the fidelity of the reproduced sound with respect to the source sound. If the reproduced sound is very close to the source sound, the equipment is classified as "hi-fi," or "high fidelity." By thinking of the optical system of a lens as a "system for transmitting optical signals" in the same way as an audio system transmits electrical signals, it is possible to find out how accurately optical signals are transmitted as long as the frequency response of the optical system can be measured. In an optical system, the equivalent of frequency is "spatial frequency," which indicates how many patterns, or cycles, of a certain sine density are present in a 1 mm width. Accordingly, the unit of spatial frequency is lines per mm. Figure-27-A shows the MTF characteristics of an ideal "hi-fi" lens for a certain spatial frequency, with the output equal to the input. A lens of this type is said to provide a contrast of 1:1. However, since actual lenses contain residual aberration, actual contrast ratios are always less than 1:1. As the spatial frequency increases (i.e., as the black-and-white sine wave pattern becomes finer, or more dense), the contrast decreases as shown in Figure-27-D until finally becoming gray with no distinction between black and white (no contrast, 1:0) at the spatial frequency limit. Illustrating this phenomenon in graph form with spatial frequency as the horizontal axis and contrast as the vertical axis results in the curve shown in Graph-4. In other words, the graph makes it possible to check resolution and contrast reproducibility (i,e., the degree of modulation) in a continuous manner. However, since it only shows the characteristics for one point in the image area, it is necessary to use data for several points in order to determine the MTF characteristics of the overall image. Because of this, for the EF lens MTF characteristics presented in this book, two typical spatial frequencies (10 lines/mm and 30 lines/mm) are selected and sophisticated computer simulation techniques are used to determine the MTF characteristics of the entire image area, graphed with the horizontal axis corresponding to the distance from the center of the image along the diagonal line, and the vertical axis corresponding to contrast.

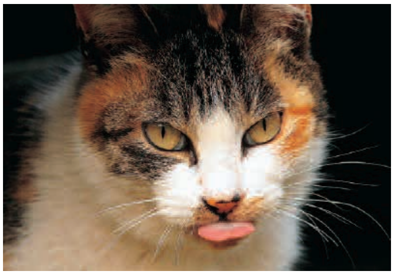
How to read the MTF graphs

The MTF graphs shown for the lenses in this book place image height (with the image center having an image height of 0) on the horizontal axis and contrast on the vertical axis. MTF characteristics are provided for spatial frequencies of 10 lines/mm and 30 lines/mm. The test chart's spatial frequency, lens aperture value and direction in the image area are as shown in the following table.

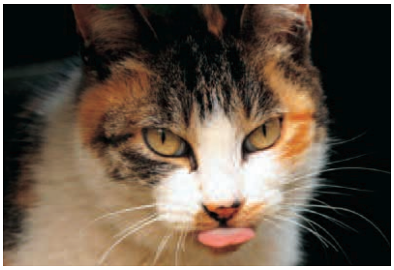
Basic information on the performance of a lens can be extracted from the MTF chart as follows: The closer the 10-line/mm curve is to 1, the better the contrast and separation ability of the lens, and the closer the 30-line/mm curve is to 1, the better the resolving power and sharpness of the lens. Additionally, the closer the characteristics of M and S are, the more natural the background blur becomes. Although a good balance between these characteristics is important, it can generally be assumed that a lens will provide excellent image quality if the 10-line/mm curve is greater than 0.8, and that satisfactory image quality can be obtained if the l0-line/mm curve is greater than 0.6. Looking at the MTF characteristics of EF super-telephoto L-series lenses with this frame of reference, it is obvious from just the data that these lenses possess extremely high-performance imaging characteristics.

Graph-4 MTF Characteristics for A Single Image Point

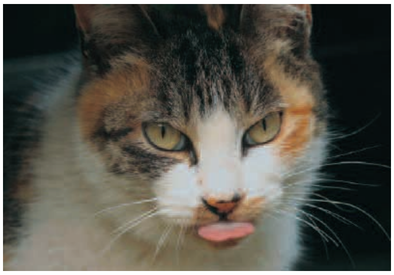




A:Resolving power and contrast are both good



B:Contrast is good and resolving power is bad

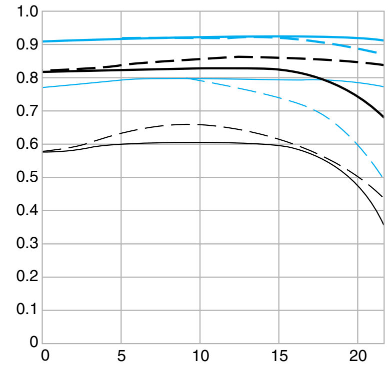


C:Resolving power is good and contrast is bad

Table-3

Spatial frequency	Maximum aperture		F 8	
	S	M	S	M
10 lines/mm	——	– –	——	– –
30 lines/mm	——	– –	——	– –

Graph-5 MTF Characteristics



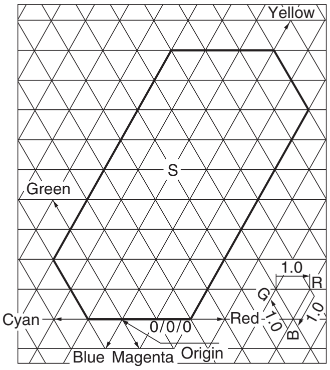
Colour balance

The colour reproduction fidelity of a photo taken through a lens compared to the original subject. Colour balance in all EF lenses is based on ISO recommended reference values and maintained within a strict tolerance range narrower than ISO's CCI allowable value range.→ CCI

CCI (colour contribution index)

Colour reproduction in a colour photograph depends on three factors: the colour characteristics of the film or digital imaging system, the colour temperature of the light source illuminating the subject, and the light transmission characteristics of the lens. The colour contribution index, or CCI, is an index indicating "the amount of colour variation caused by filtering effect differences between lenses" when using a standard film and light source, and is expressed by three numbers in the form 0/5/4. These three numbers are relative values expressed as logarithms of lens transmittance at the blue-violet/green/red wavelengths corresponding to the three light sensitive emulsion layers of colour film, with larger numbers representing higher transmittance. However, since photographic lenses absorb most ultraviolet wavelengths, the blue-violet transmittance value is usually zero, so colour balance is judged by comparing the green and red values to ISO-specified reference lens values. The ISO reference lens light transmission characteristics were set according to a method proposed by Japan which involved taking the average transmittance values of 57 standard lenses comprising five models from representative lens manufacturers including Canon. The resulting recommended reference value of 0/5/4 is used by film manufacturers as a reference when designing the colour production characteristics of colour films. In other words, if the light transmission characteristics of a lens do not match the ISO reference values, the colour reproduction characteristics of a colour film cannot be obtained as intended by the manufacturer.

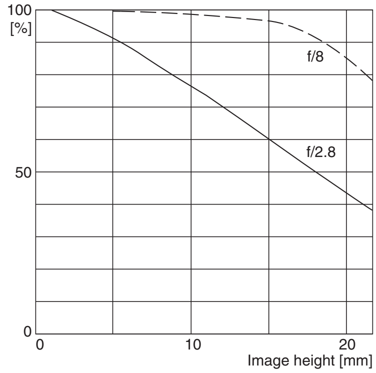
Graph-6 ISO Tolerance Range Graphed on CCI Coordinates



Peripheral illumination

The brightness of a lens is determined by the F number, but this value only indicates the brightness at the optical axis position, i.e., at the center of the image. The brightness (image surface illuminance) at the edge of the image is called peripheral illumination and is expressed as a percent (%) of the amount of illumination at the image center. Peripheral illumination is affected by lens vignetting and the cos4 (cosine 4) law and is inevitably lower than the center of the image.→ Vignetting, Cos4 law

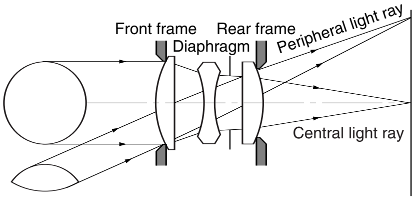
Graph-7 Image Plane Illuminance Ratio Showing the Peripheral Illumination Characteristics



Optical vignetting

Light rays entering the lens from the edges of the picture area are partially blocked by the lens frames in front of and behind the diaphragm, preventing all the rays from passing through the effective aperture (diaphragm diameter) and causing light fall-off in the peripheral areas of the image. This type of vignetting can be eliminated by stopping down the lens.

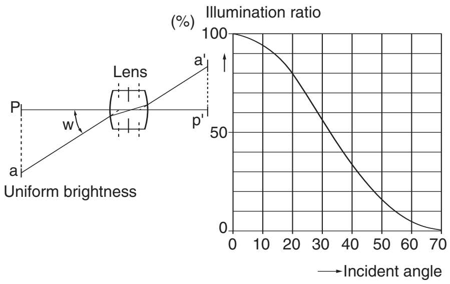
Figure-28 Vignetting



Cosine law

The cosine law, also called the cosine law, states that light fall-off in peripheral areas of the image increases as the angle of view increases, even if the lens is completely free of vignetting. The peripheral image is formed by groups of light rays entering the lens at a certain angle with respect to the optical axis, and the amount of light fall-off is proportional to the cosine of that angle raised to the

Graph-8 Peripheral Light Reduction According to Cosine Law



fourth power. As this is a law of physics, it cannot be avoided. However, with wide-angle lenses having a large angle of view, decreases in peripheral illumination can be prevented by increasing the lens' aperture efficiency (ratio of the area of the on-axis entrance pupil to the area of the off-axis entrance pupil).

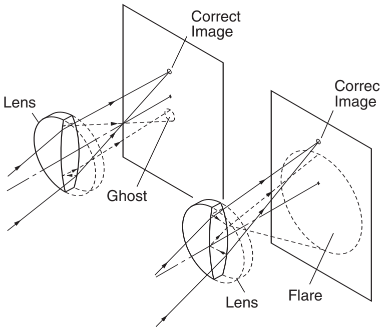
Hard vignetting

A phenomenon where light entering the lens is partially blocked by an obstruction such as the end of a lens hood or the frame of a filter, causing the corners of the image to darken or the overall image to lighten. Shading is the general term used for the case where the image is degraded by some type of obstacle that blocks light rays which should actually reach the image.

Flare

Light reflected from lens surfaces, the inside of the lens barrel and the inner walls of the camera's mirror box can reach the film or image sensor and fog part or all of the image area, degrading image sharpness. These harmful reflections are called flare. Although flare can be reduced to a large extent by coating the lens surfaces and using anti-reflection measures in the lens barrel and camera, flare cannot be completely eliminated for all subject conditions. It is therefore desirable to use an appropriate lens hood whenever possible. The term "flare" is also used when referring to the effects of blurring and halo caused by spherical and comatic aberration.

Figure-29 Flare and Ghosting



Ghost image

A type of flare occurring when the sun or other strong light source is included in the scene and a complex series of reflections among the lens surfaces causes a clearly defined reflection to appear in the image in a position symmetrically opposite the light source. This phenomenon is differentiated from flare by the term "ghost" due to its ghost-like appearance. Ghost images caused by surface reflections in front of the aperture have the same shape as the aperture, while a ghost image caused by reflections behind the aperture appears as an out-of-focus area of light fogging. Since ghost images can also be caused by strong light sources outside the picture area, use of a hood or other shading device is recommended for blocking undesired light. Whether or not ghosting will actually occur when the picture is taken can be verified beforehand by looking through the viewfinder and using the camera's depth-of-field check function to close down the lens to the actual aperture to be used during exposure.

Coating

When light enters and exits an uncoated lens, approximately 5% of the light is reflected back at each lens-air boundary due to the difference in index of refraction. This not only reduces the amount of light passing through the lens but can also lead to repeating reflections which can cause unwanted flare or ghost images. To prevent this reflection, lenses are processed with a special coating. Basically this is carried out using vacuum vapor deposition to coat the lens with a thin film having a thickness 1/4 the wavelength of the light to be affected, with the film made of a substance (such as magnesium fluoride) which has an index of refraction of $\sqrt{n}$, where n is the index of refraction of the lens glass. Instead of a single coating affecting only a single wavelength, however, EF lenses feature a superior multi-layer coating (multiple layers of vapor deposited film reducing the reflection rate to 0.2~0.3%) which effectively prevents reflections of all wavelengths in the visible light range. Lens coating is carried out not only to prevent reflections, however. By coating the various lens elements with appropriate substances having different properties, coating plays an important role in providing the overall lens system with optimum colour balance characteristics.

Optical Glass

Optical Glass

Optical glass is specially made for use in precision optical products such as photographic lenses, video lenses, telescopes and microscopes. In contrast to general-purpose glass, optical glass is provided with fixed, precise refraction and dispersion characteristics (precision to six decimal points) and subjected to strict requirements regarding transparency and lack of defects such as striae, warps and bubbles. Types of optical glass are classified according to their composition and optical constant (Abbe number), and more than 250 types are in existence today. For high-performance lenses, different types of optical glass are optimally combined. Glass with an Abbe number of 50 or less is called flint glass (F), and glass with an Abbe number of 55 or more is called crown glass (K). Each type of glass is further classified in other ways such as specific gravity, and a corresponding serial name is assigned to each type.

Abbe number

A numerical value indicating the dispersion of optical glass, using the Greek symbol ν. Also called the optical constant. The Abbe number is determined by the following formula using the index of refraction for three Fraunhofer's lines: F (blue), d (yellow) and c (red).

Abbe number = $\nu d = nd - 1/nF - nc$

Fraunhofer's lines

Absorption lines discovered in 1814 by a German physicist named Fraunhofer (1787~1826), comprising the absorption spectrum present in the continuous spectrum of light emitted from the sun created by the effect of gases in the sun's and earth's atmospheres. Since each line is located at a fixed wavelength, the lines are used for reference in regard to the colour (wavelength) characteristics of optical glass. The index of refraction of optical glass is measured based on nine wavelengths selected from among Fraunhofer's lines (see Table 4). In lens design, calculations for correcting chromatic aberrations are also based on these wavelengths.

Table-4 Light Wavelengths and Spectrum Lines

Spectrum line code	i	h	g	F
Wavelength (mm)	365,0	404,7	435,8	486,1
Colour	Ultra-violet	Violet	Blue-violet	Blue

Spectrum line code	e	d	c	r	t
Wavelength (mm)	546,1	587,6	656,3	706,5	1014
Colour	Green	Yellow	Red	Red	Infrared

Note: 1 nm = 10^{-6}mm

Fluorite

Fluorite has extremely low indexes of refraction and dispersion compared to optical glass and features special partial dispersion characteristics (extraordinary partial dispersion), enabling virtually ideal correction of chromatic aberrations when combined with optical glass. This fact has long been known, and in 1880 natural fluorite was already in practical use in the apochromatic objective lenses of microscopes. However, since natural fluorite exists only in small pieces, it cannot be used practically in photographic lenses. In answer to this problem, Canon in 1968 succeeded in establishing production technology for manufacturing large artificial crystals, thus opening the door for fluorite use in photographic lenses.

UD lens

A lens made of special optical glass possessing optical characteristics similar to fluorite. UD lens elements are especially effective in correcting chromatic aberrations in super-telephoto lenses. Two UD lens elements are characteristically equivalent to one fluorite element. "UD" stands for "ultra-low dispersion."

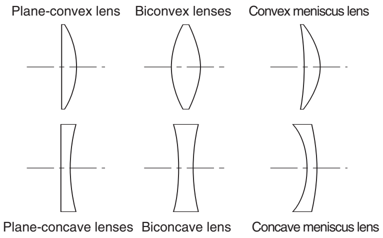
Lead-Free Glass

This is a type of optical glass which contains no lead, to relieve the burden on the environment. Lead is used in many types of optical glass because it raises the refractive power of glass. While the lead cannot leak out of the glass it is contained in, it does nevertheless pose a threat to the environment when it escapes in the form of waste produced when grinding and polishing the glass. With the goal of eliminating lead from the manufacturing process, Canon worked with a glass manufacturer to develop lead free glass, and is in the process of phasing out glass which contains lead from its lens lineup. Lead free glass uses titanium, which, unlike lead, poses no problems for the environment or humans, but still delivers optical characteristics equal to conventional leaded glass.

Lens shapes and lens construction fundamentals

Lens shapes

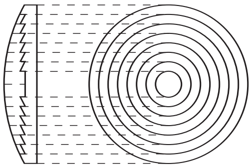
Figure-30 Lens Shapes



Fresnel lens

A type of converging lens, formed by finely dividing the convex surface of a flat convex lens into many concentric circle-shaped ring lenses and combining them to extremely reduce the thickness of the lens while retaining its function as convex lens. In an SLR, to efficiently direct peripheral diffused light to the eyepiece, the side opposite the matte surface of the focusing screen is formed as a fresnel lens with a 0.05 mm pitch Fresnel lenses are also commonly used in flash units, indicated by the concentric circular lines visible on the white diffusion screen covering the flash tube. The projection lens used to project light from a lighthouse is an example of a giant fresnel lens.

Figure-31 Fresnel Lens



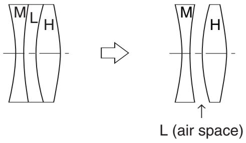
Aspherical lens

Photographic lenses are generally constructed of several single lens elements, all of which, unless otherwise specified, have spherical surfaces. Because all surfaces are spherical, it becomes especially difficult to correct spherical aberration in large-aperture lenses and distortion in super-wide-angle lenses. A special lens element with a surface curved with the ideal shape to correct these aberrations, i.e., a lens having a free-curved surface which is not spherical, is called an aspherical lens. The theory and usefulness of aspherical lenses. have been known since the early days of lens making, but due to the extreme difficulty of actually processing and accurately measuring aspherical surfaces, practical aspherical lens manufacturing methods were not realised until fairly recently. The first SLR photographic lens to incorporate a large diameter aspherical lens was Canon's FD 55mm f/1.2AL released in March 1971. Due to revolutionary advances in production technology since that time, Canon's current EF lens group makes abundant use of various aspherical lens types such as ground and polished glass aspherical lens elements, ultra-precision glass molded (GMo) aspherical lens elements, composite aspherical lens elements and replica aspherical lens elements.

Air lens

The air spaces between the glass lens elements making up a photographic lens can be thought of as lenses made of glass having the same index of refraction as air (1.0). An air space designed from the beginning with this concept in mind is called an air lens. Since the refraction of an air lens is opposite that of a glass lens, a convex shape acts as a concave lens and a concave shape acts as a convex lens. This principle was first propounded in 1898 by a man named Emil von Hoegh working for the German company Goerz.

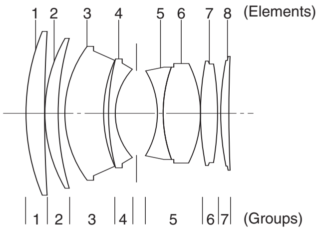
Figure-32 Air Lens Concept Diagram



Actual photographic lenses

When looking at the enlarged image of an object through a magnifying glass, it is common for the edges of the image to be distorted or discoloured even if the center is clear. As this indicates, a single-element lens suffers from many types of aberrations and cannot reproduce an image which is clearly defined from corner to corner. Because of this, photographic lenses are constructed of several lens elements having different shapes and characteristics in order to obtain a sharp image over the entire picture area. The basic construction of a lens is listed in the specifications section of brochures and instruction manual in terms of elements and groups. Figure 33 shows an example of the EF 85mm f/1.2L II USM, constructed of 8 elements in 7 groups.

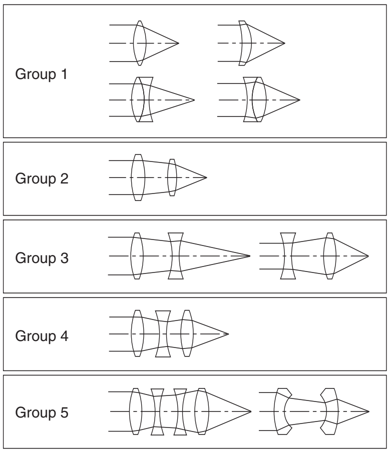
Figure-33 EF 85mm f/1.2L Ⅱ USM Lens Construction



Fundamentals of lens construction

There are five basic constructions used for general-purpose single focal length lenses. ① The single type is the simplest — comprised of a single element or a doublet made of two conjoined elements. ② and ③ are of the double type, comprised of two independent elements. ④ is a triplet type, comprised of three independent lens elements in a convex-concave-convex sequence. ⑤ is a symmetrical type, consisting of two groups of one or more lenses of the same shape and configuration symmetrically oriented around the diaphragm.

Figure-34 Fundamental Lens Groupings



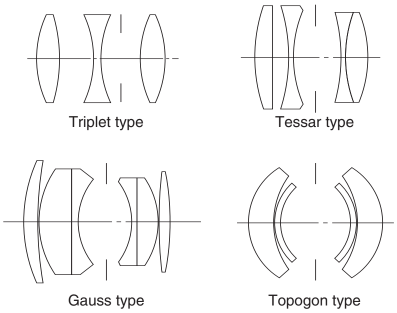
Typical photographic lens types

● Single focal length lenses

① Symmetrical type

In this type of lens, the lens group behind the diaphragm has nearly the same configuration and shape as the lens group in front of the diaphragm. Symmetrical lenses are further classified into various types such as the Gauss type, triplet type, Tessar type, Topcon type and orthometer type. Of these, the Gauss type and its derivations is the most typical configuration used today because its symmetrical design allows well balanced correction of all type of aberrations, and a comparatively long back focus can be achieved. The Canon 50mm f/1.8 released back in 1951 succeeded in eliminating the comatic aberration which was the sole weak point of Gauss type lenses of that day, and thus became famous as a historical landmark lens due to the remarkable improvement in performance it afforded. Canon still uses a Gauss type construction in current lenses such as the EF 50mm f/1.4 USM, EF 50mm f/1.8 II and EF 85mm f/1.2L II USM. The Tessar and triplet type symmetrical configurations are commonly used today in compact cameras equipped with single focal length lenses.

Figure-35 Typical Photographic Lens Types


Triplet type
Tessar type
Gauss type
Topogon type

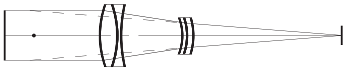
② Telephoto type (teletype)

With general photographic lenses, the overall length of a lens (the distance from the apex of the frontmost lens element to the focal plane) is longer than its focal length. This is not usually the case with lenses of particularly long focal length, however, since using a normal lens construction would result in a very large, unwieldy lens. To keep the size of such a lens manageable while still providing a long focal length, a concave (negative) lens assembly is placed behind the main convex (positive) lens assembly, resulting in a lens which is shorter than its focal length. Lenses of this type are called telephoto lenses. In a telephoto lens, the second principal point is located in front of the frontmost lens element.

● Telephoto ratio

The ratio between the overall length of a telephoto lens and its focal length is called the telephoto ratio. Put another way, it is the value of the distance from the apex of the frontmost lens element to the focal plane divided by the focal length. For telephoto lenses, this value is less than one. For reference, the telephoto ratio of the EF 300mm f/2.8L IS USM is 0.94, and that of the EF 600mm f/4L IS USM is 0.81.

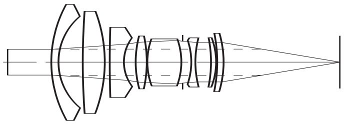
Figure-36 Telephoto Type



③ Retrofocus type

Conventionally designed wide-angle lenses have such a short back focus that they cannot be used in SLR cameras because they would obstruct the up/down swinging movement of the main mirror. Because of this, wide-angle lenses for SLRs have a construction opposite that of telephoto lenses, with a negative lens assembly placed in front of the main lens assembly. This moves the second principal point behind the lens (between the rearmost lens element and the film plane) and creates a lens having a back focus which is longer than the focal length. This type of lens is generally called a retrofocus lens from the name of a product marketed by Angenieux Co. of France. In optical terms, this type of lens is classified as an inverted telephoto type lens.

Figure-37 Inverted Telephoto Types (Retrofocus)



Zoom lenses

④ 4-group zoom type

An orthodox zoom lens configuration which clearly divides the functions of the lens into four groups (focusing group, magnification variation group, correction group and image formation group). Two groups –– the magnification variation group and correction group –– move during zooming. Since a high-magnification zoom ratio can be easily obtained with this type of construction, it is commonly used for movie camera lenses and SLR telephoto zoom lenses. However, due to problems incurred when designing compact zoom lenses, its use is becoming less common in modern non-telephoto zoom lenses.

⑤ Short zoom type

Explanation → P.175

⑥ Multi-group zoom type

Explanation → P.175

Focusing and lens movement

Focusing and lens movement techniques

Methods of lens movement for focusing can be broadly classified into the five types described below.

① Overall linear extension

The entire lens optical system moves straight backward and forward when focusing is carried out. This is the simplest type of focusing used in mainly in wide-angle through standard single focal length lenses, Such as the EF 15mm f/2.8 Fisheye, lense, the EF 50mm f/1.4 USM, the TS-E 90mm f/2.8, and other EF lenses.

② Front group linear extension

The rear group remains fixed and only the front group moves straight backward and forward during focusing. Examples of front group linear extension lenses are the EF 50mm f/2.5 Compact Macro, MP-E 65mm f/2.8 Macro Photo and EF 85mm f/1.2L II USM.

③ Front group rotational extension

The lens barrel section holding the front lens group rotates to move the front group backward and forward during focusing. This type of focusing is used only in zoom lenses and is not found in single focal length lenses. Representative examples of lenses using this method are the EF 28-90mm f/4-5.6 III, EF 75-300mm f/4-5.6 IS USM and EF 90-300mm f/4.5-5.6 USM and other EF lenses.

④ Inner focusing

Focusing is performed by moving one or more lens groups positioned between the front lens group and the diaphragm.
→ P.176

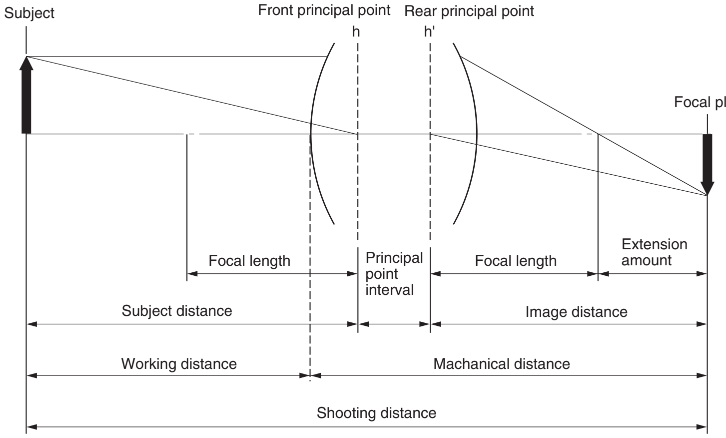
⑤ Rear focusing

Focusing is performed by moving one or more lens groups positioned behind the diaphragm. → P.177

Floating system

This system varies the interval between certain lens elements in accordance with the extension amount in order to compensate for aberration fluctuation caused by camera distance. This method is also referred to as a close-distance aberration compensation mechanism. → P.177

Figure-38 Shooting Distance, Subject Distance and Image Distance



Shooting distance/subject distance/image distance

Camera distance

The distance from the focal plane to the subject. The position of the focal plane is indicated on the top of most cameras by a "⊖" symbol.

Subject distance

The distance from the lens' front principal point to the subject.

Image distance

The distance from the lens' rear principal point to the focal plane when the lens is focused on a subject at a certain distance.

Extension amount

With a lens which moves the entire optical system backward and forward during focusing, the amount of lens movement necessary to focus a subject at a limited distance from the infinity focus position.

Mechanical distance

The distance from the front edge of the lens barrel to the focal plane.

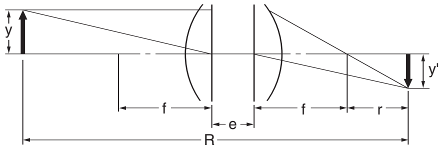
Working distance

The distance from the front edge of the lens barrel to the subject. An important factor especially when shooting close-ups and enlargements.

Image magnification

The ratio (length ratio) between the actual subject size and the size of the image reproduced on film. A macro lens with a magnification indication of 1:1 can reproduce an image on film the same size as the original subject (actual size). Magnification is generally expressed as a proportional value indicating the size of the image compared to the actual subject. (For example, a magnification of 1:4 is expressed as 0.25x.)

Figure-39 Relationship Between the Focal Length, Extension Amount (Overall Extension) and Magnification



$$R = \frac{(r+f)^2}{r} + e = \frac{f(M+1)^2}{M} + e$$

$$M = \frac{y'}{y} = \frac{r'}{f}$$

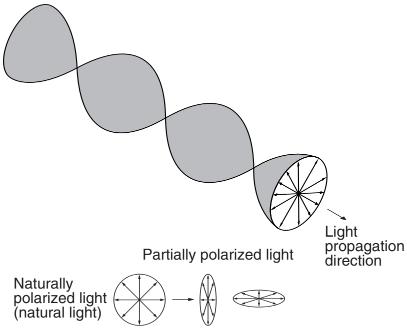
f = Focal length
r = Extension amount
e = Principal point interval
R = Shooting distance
y = Subject size
y' = Subject size on the film plane
M = Magnification

Polarized light and polarizing filters

Polarized light

Since light is a type of electromagnetic wave, it can be thought of as uniformly vibrating in all directions in a plane perpendicular to the direction of propagation. This type of light is called natural light (or natural polarized light). If the direction of vibration of natural light becomes polarized for some reason, that light is called polarized light. When

Figure-40 Naturally Polarized Electromagnetic Wave



natural light is reflected from the surface of glass or water, for example, the reflected light vibrates in one direction only and is completely polarized. Also, on a sunny day the light from the area of the sky at a 90° angle from the sun becomes polarized due to the effect of air molecules and particles in the atmosphere. The half-mirrors used in autofocus SLR cameras also cause light polarization.

Linear polarizing filter

A filter which only passes light vibrating in a certain direction. Since the vibrational locus of the light allowed to pass through the filter is linear in nature, the filter is called a linear polarizing filter. This type of filter eliminate reflections from glass and water the same way as a circular polarizing filter, but it cannot be used effectively with most auto exposure and autofous cameras as it will cause exposure errors in AE cameras equipped with TTL metering systems using half-mirrors, and will cause focusing errors in AF cameras incorporating AF range-finding systems using half-mirrors.

Circular polarizing filter

A circular polarizing filter is functionally the same as a linear polarizing filter as it only passes light vibrating in a certain direction. However, the light passing through a circular polarizing filter differs from light passing through a linear polarizing filter in that the vibrational locus rotates in a spiral pattern as it propagates. Thus, the effect of the filter does not interfere with the effect of half-mirrors, allowing normal operation of TTL-AE and AF functions. When using a polarizing filter with an EOS camera, be sure to always use a circular polarizing filter. The effectiveness of a circular polarizing filter in eliminating reflected light is the same as that of a linear polarizing filter.

Digital Terminology

Image sensor

A semiconductor element which converts image data into an electric signal, playing the role of the film in a regular film camera. Also known as an imager. The two most common image elements used in digital cameras are CCD (Charge-Coupled Devices) and CMOS (Complementary Metal-Oxide Semi-conductors). Both are area sensors containing a large number of receptors (pixels) on a flat surface which convert variations in light into electric signals. The higher the number of receptors, the more accurate the image reproduction is. Since these receptors are only sensitive to brightness and not colour, RGB or CMYG colour filters are placed before them in order to capture both brightness and colour data at the same time.

Low-pass filter

With general image elements used in digital cameras, RGB or CMYG colour information is collected for each receptor arranged on the surface. This means that when light with a high spatial frequency hits a single pixel, false colours, moiré, and other colours which do not exist in the subject appear in the image. In order to reduce the occurrence of these types of false colours, the light must made to enter many different receptors, and in order to do that, the receptors used are low-pass filters. Low-pass filters use liquid crystal and other crystal structures which are characterised by double refraction (a phenomenon where two streams of refracted light are created), placed before the image elements. By double-refracting light with a high spatial frequency using low-pass filters, it becomes possible to receive light using multiple elements.

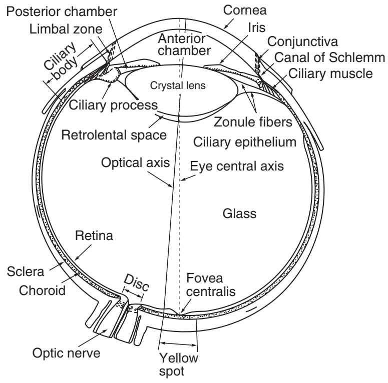
The human eye and viewfinder diopter

Eyesight, visual acuity

The ability of the eye to distinguish details of an object's shape. Expressed as a numerical value which indicates the inverse of the minimum visual angle at which the eye can clearly distinguish two points or lines, i.e. the resolution of the eye in reference to a resolution of 1'. (Ratio with a resolution of 1' assumed as 1.)

Eye accommodation

Figure-41 Human Eye Construction



The ability of the eye to vary its refractive power in order to form an image of an object on the retina. The state in which the eye is at its minimum refractive power is called the accommodation rest state.

Normal vision, emmetropia

The eye condition in which the image of an infinitely distant point is formed on the retina when the eye is in the accommodation rest state.

Far-sightedness

The eye condition in which the image of an infinitely distant point is formed to the rear of the retina when the eye is in the accommodation rest state.

Near-sightedness, myopia

The eye condition in which the image of an infinitely distant point is formed in front of the retina when the eye is in the accommodation rest state.

Astigmatism

The eye condition in which astigmatism exists on the eye's visual axis.

Presbyopia

The eye condition in which the ability of the eye to focus decreases as a person becomes older. In camera terms, this is similar to having a fixed focal point with a shallow depth of field.

Least distance of distinct vision

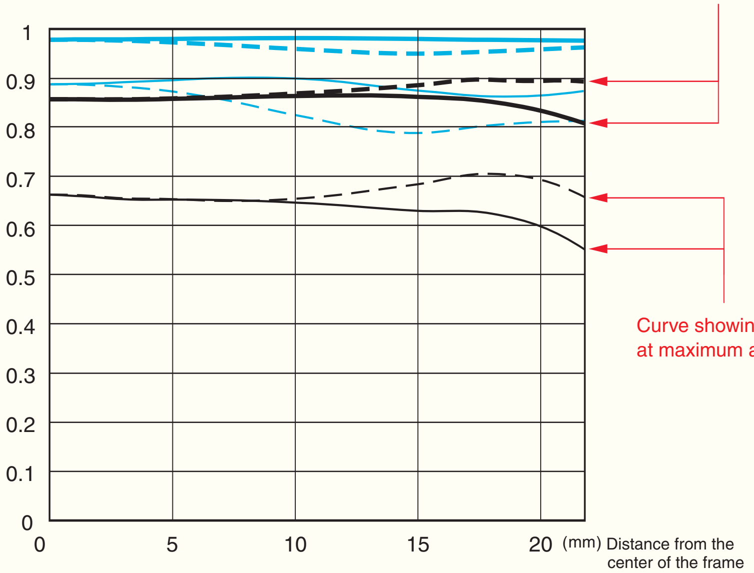
The closest distance at which an eye having normal vision can observe an object without straining. This distance is normally assumed to be 25 cm/0.8 ft.

Diopter

The degree to which the light ray bundles leaving the viewfinder converge or disperse. The standard diopter of all EOS cameras is set at –1 dpt. This setting is designed to allow the finder image to appear to be seen from a distance of 1 m. Thus, if a person cannot see the viewfinder image clearly, the person should attach to the camera's eyepiece a dioptric adjustment lens having a power which, when added to the viewfinder's standard diopter, makes it possible to easily see an object at one meter. The numerical values printed on EOS dioptric adjustment lenses indicate the total diopter obtained when the dioptric adjustment lens is attached to the camera.

MTF Characteristics

How to read the MTF Characteristics



An MTF characteristic of 0.8 or more at 10 lines/mm indicates a superior lens.

An MTF characteristic of 0.6 or more at 10 lines/mm indicates a satisfactory image.

Curve showing contrast at maximum aperture

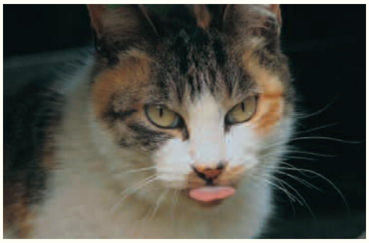
Curve showing resolution at maximum aperture

Spatial frequency	Maximum aperture		f/8	
	S	M	S	M
10 lines/mm	▬▬▬	■■■■■■	▬▬▬	■■■■■■
30 lines/mm	───	------	───	------

The more the S and M curves are in line, the more natural the blurred image becomes.

Resolving power and contrast are both good

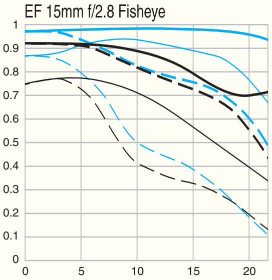
Contrast is good and resolving power is bad



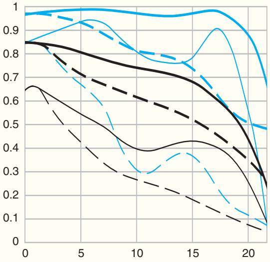
Resolving power is good and contrast is bad

Single Focal Length Lenses

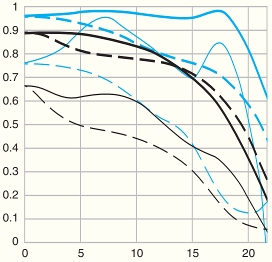
EF 15mm f/2.8 Fisheye



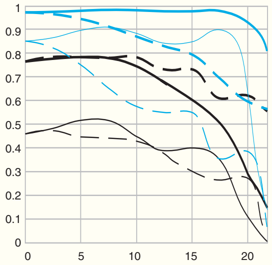
EF 14mm f/2.8L USM



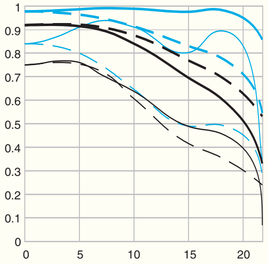
EF 20mm f/2.8 USM



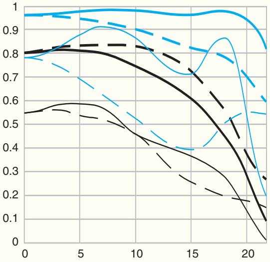
EF 24mm f/1.4L USM



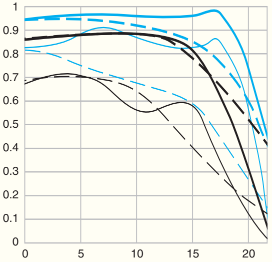
EF 24mm f/2.8



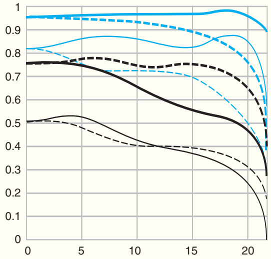
EF 28mm f/1.8 USM



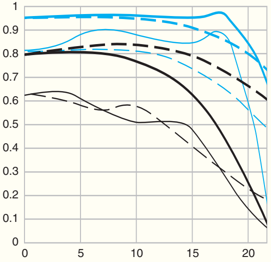
EF 28mm f/2.8



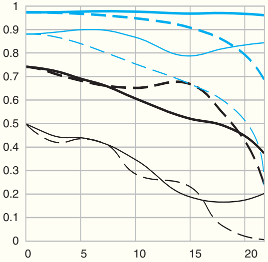
EF 35mm f/1.4L USM



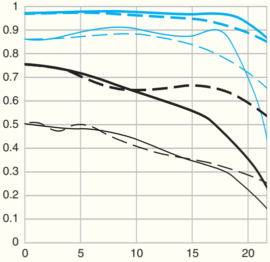
EF 35mm f/2



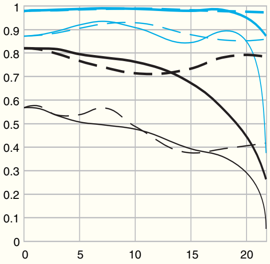
EF 50mm f/1.2L USM



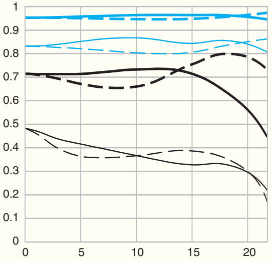
EF 50mm f/1.4 USM



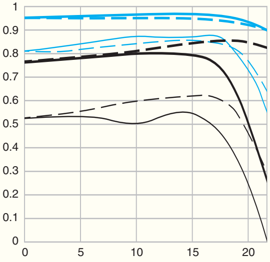
EF 50mm f/1.8 Ⅱ



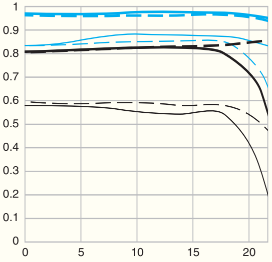
EF 85mm f/1.2L Ⅱ USM



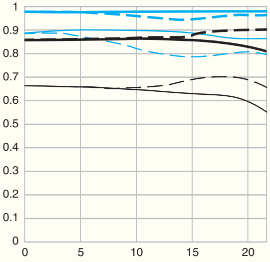
EF 85mm f/1.8 USM



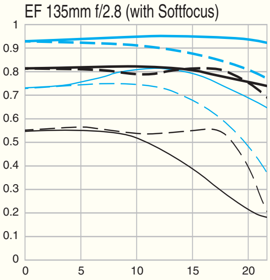
EF 100mm f/2 USM



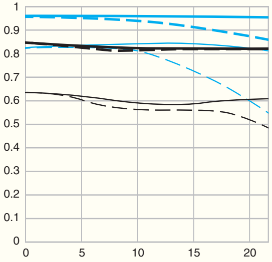
EF 135mm f/2L USM



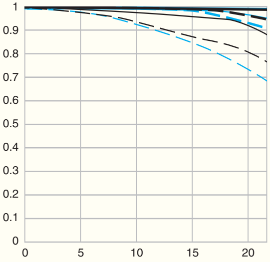
EF 135mm f/2.8 (with Softfocus)



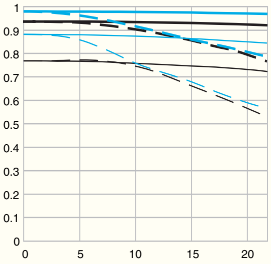
EF 200mm f/2.8L Ⅱ USM



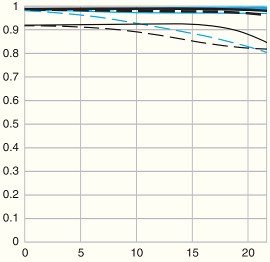
EF 300mm f/2.8L IS USM



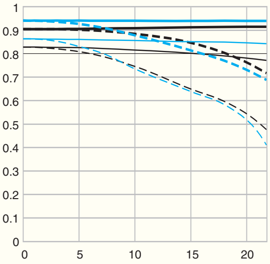
EF 300mm f/4L IS USM



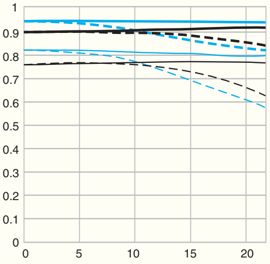
EF 400mm f/2.8L IS USM



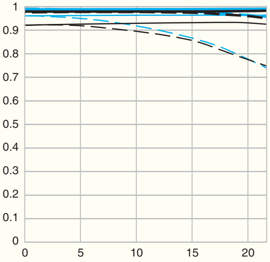
EF 400mm f/4 DO IS USM

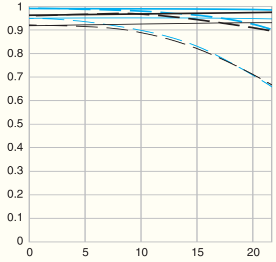


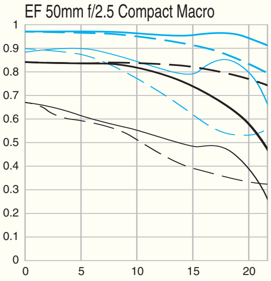
EF 400mm f/5.6L USM

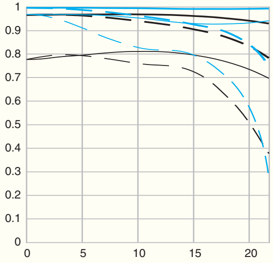


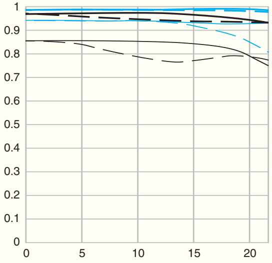
EF 500mm f/4L IS USM

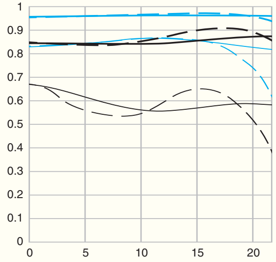


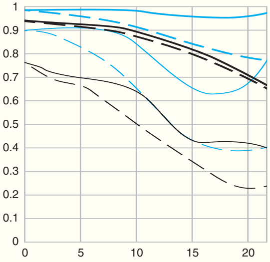

EF 600mm f/4L IS USM

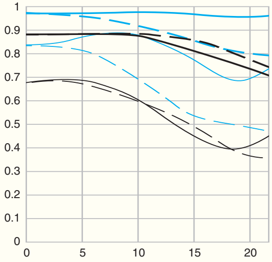

EF 50mm f/2.5 Compact Macro

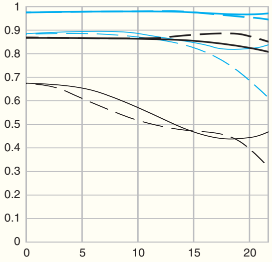

EF 100mm f/2.8 Macro USM

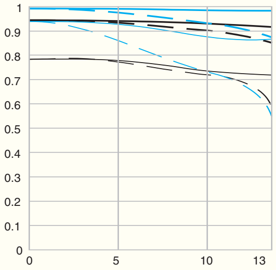

EF 180mm f/3.5L Macro USM


MP-E 65mm f/2.8 1-5 x Macro Photo

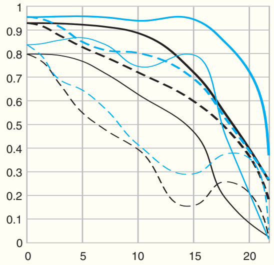

TS-E 24mm f/3.5L

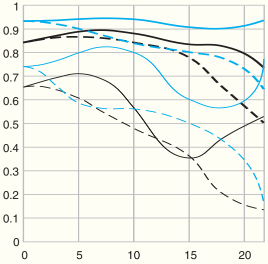

TS-E 45mm f/2.8

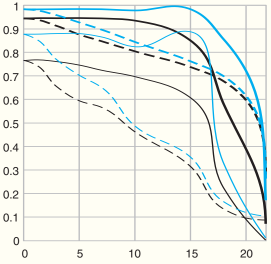

TS-E 90mm f/2.8

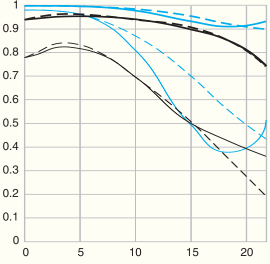

EF-S 60mm f/2.8 Macro USM

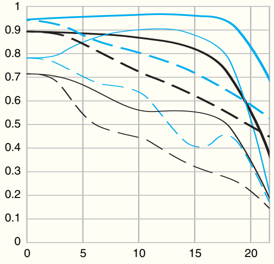
Zoom Lenses

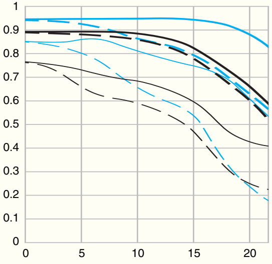

EF 16-35mm f/2.8L USM WIDE

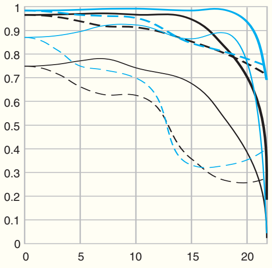

EF 16-35mm f/2.8L USM TELE

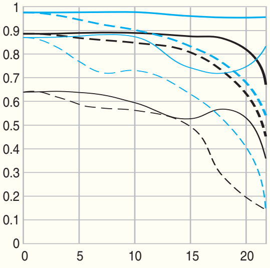

EF 17-40mm f/4L USM WIDE

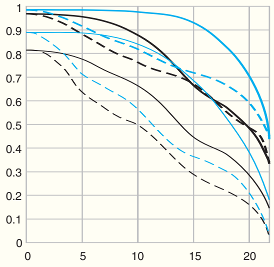

EF 17-40mm f/4L USM TELE

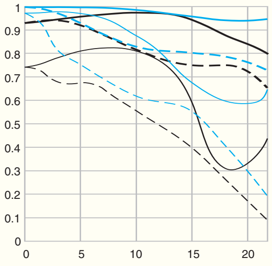

EF 20-35mm f/3.5-4.5 USM WIDE

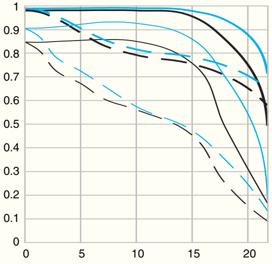

EF 20-35mm f/3.5-4.5 USM TELE

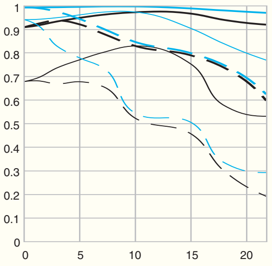

EF 24-70mm f/2.8L USM WIDE


EF 24-70mm f/2.8L USM TELE


EF 24-85mm f/3.5-4.5 USM WIDE

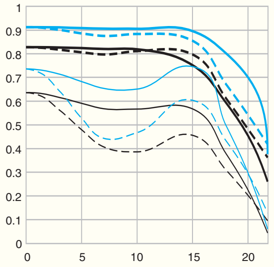

EF 24-85mm f/3.5-4.5 USM TELE


EF 24-105mm f /4L IS USM WIDE

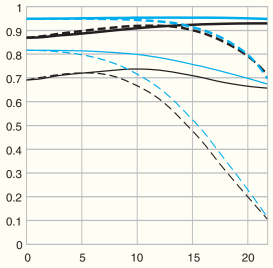

EF 24-105mm f /4L IS USM TELE

Zoom Lenses

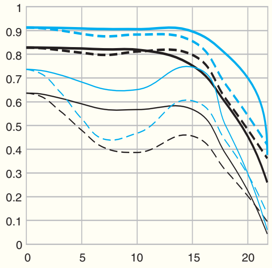
EF 28-90mm f/4-5.6 Ⅱ USM WIDE



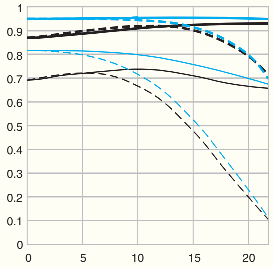
EF 28-90mm f/4-5.6 Ⅱ USM TELE



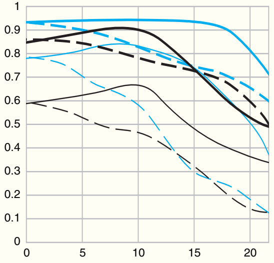
EF 28-90mm f/4-5.6 Ⅲ WIDE



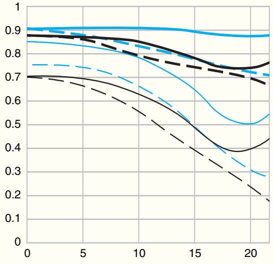
EF 28-90mm f/4-5.6 Ⅲ TELE



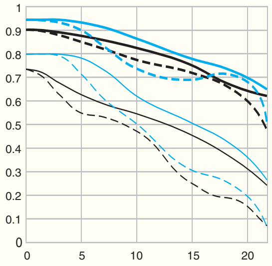
EF 28-105mm f/3.5-4.5 Ⅱ USM WIDE



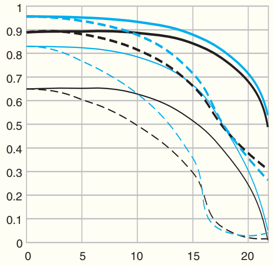
EF 28-105mm f/3.5-4.5 Ⅱ USM TELE



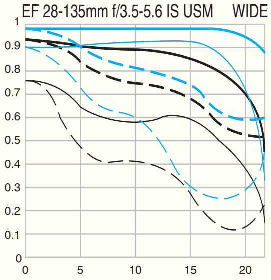
EF 28-105mm f/4-5.6 USM / EF 28-105mm f/4-5.6 WIDE



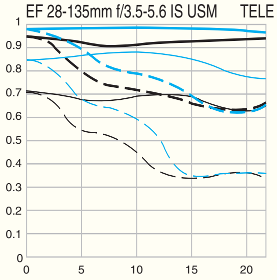
EF 28-105mm f/4-5.6 USM / EF 28-105mm f/4-5.6 TELE



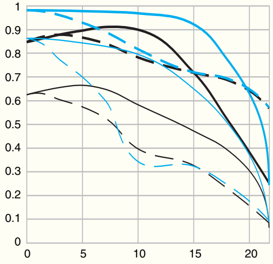
EF 28-135mm f/3.5-5.6 IS USM WIDE



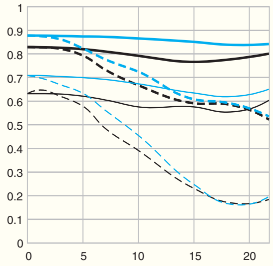
EF 28-135mm f/3.5-5.6 IS USM TELE



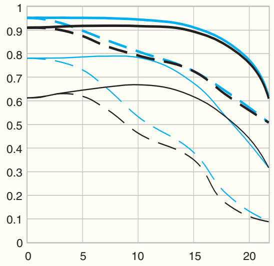
EF 28-200mm f/3.5-5.6 USM / EF 28-200mm f/3.5-5.6 WIDE



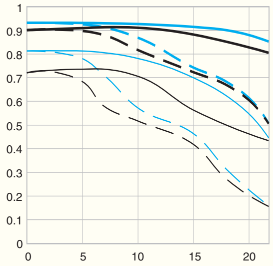
EF 28-200mm f/3.5-5.6 USM / EF 28-200mm f/3.5-5.6 TELE



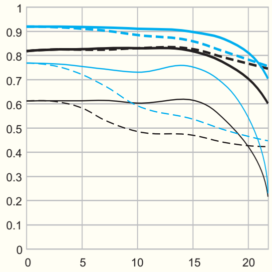
EF 28-300mm f/3.5-5.6L IS USM WIDE



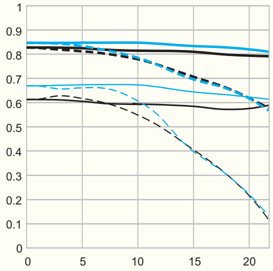
EF 28-300mm f/3.5-5.6L IS USM TELE



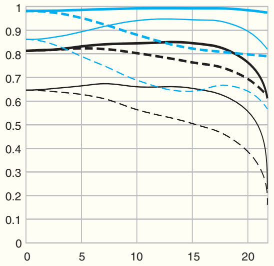
EF 55-200mm f/4.5-5.6 Ⅱ USM WIDE



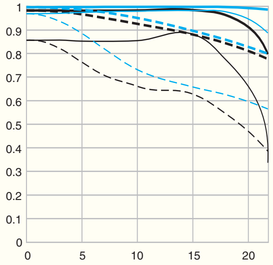
EF 55-200mm f/4.5-5.6 Ⅱ USM TELE



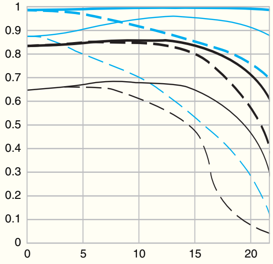
EF 70-200mm f/2.8L IS USM WIDE



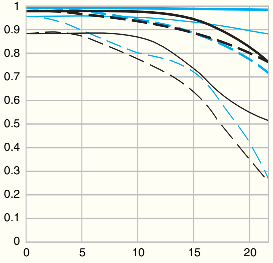
EF 70-200mm f/2.8L IS USM TELE



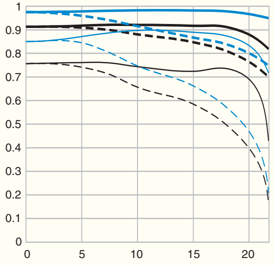
EF 70-200mm f/2.8L USM WIDE



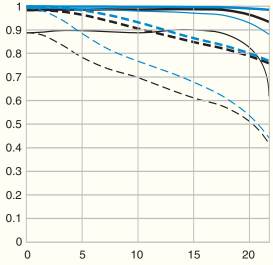
EF 70-200mm f/2.8L USM TELE



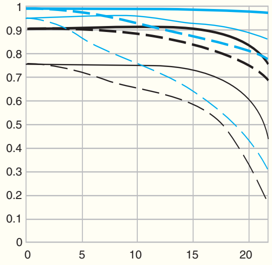
EF 70-200mm f/4L IS USM WIDE



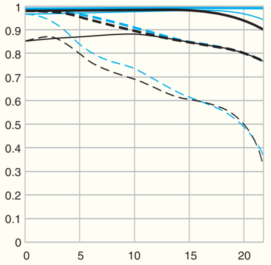
EF 70-200mm f/4L IS USM TELE



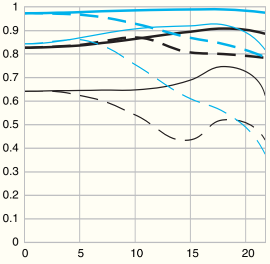
EF 70-200mm f/4L USM WIDE



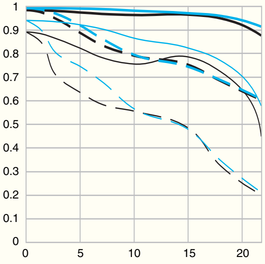
EF 70-200mm f/4L USM TELE



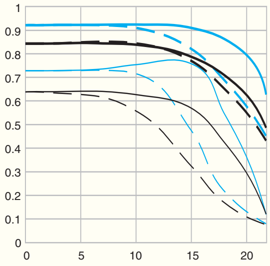
EF 70-300mm f/4-5.6 IS USM WIDE



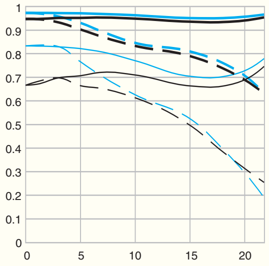
EF 70-300mm f/4-5.6 IS USM TELE



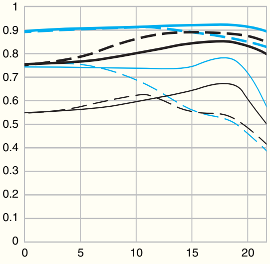
EF 70-300mm f/4.5-5.6 DO IS USM WIDE



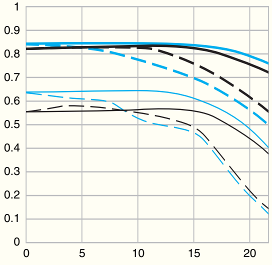
EF 70-300mm f/4.5-5.6 DO IS USM TELE



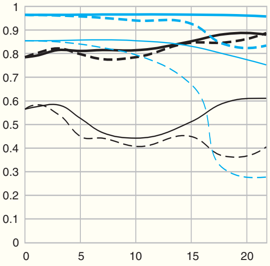
EF 75-300mm f/4-5.6Ⅲ USM / EF 75-300mm f/4-5.6Ⅲ WIDE



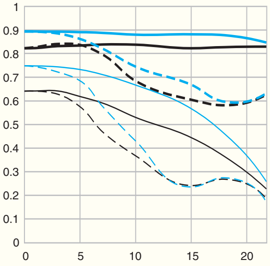
EF 75-300mm f/4-5.6Ⅲ USM / EF 75-300mm f/4-5.6Ⅲ TELE



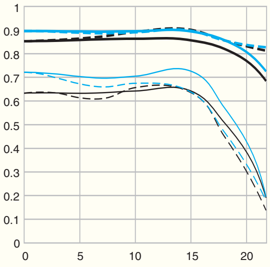
EF 80-200mm f/4.5-5.6 Ⅱ WIDE



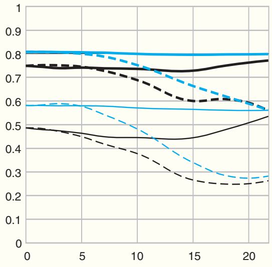
EF 80-200mm f/4.5-5.6 Ⅱ TELE



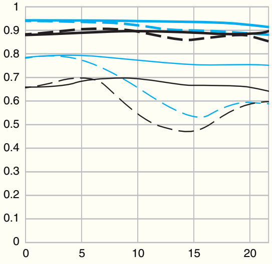
EF 90-300mm f/4.5-5.6 USM / EF 90-300mm f/4.5-5.6 WIDE



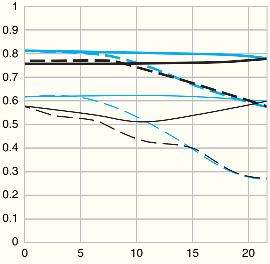
EF 90-300mm f/4.5-5.6 USM / EF 90-300mm f/4.5-5.6 TELE



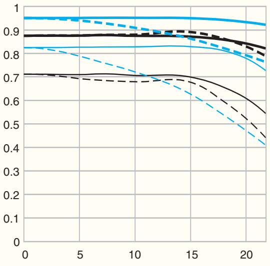
EF 100-300mm f/4.5-5.6 USM WIDE



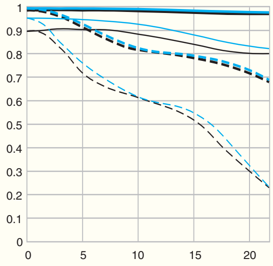
EF 100-300mm f/4.5-5.6 USM TELE



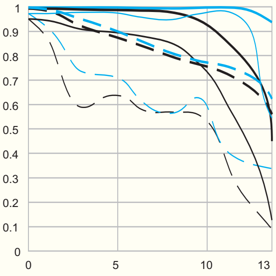
EF 100-400mm f/4.5-5.6L IS USM WIDE



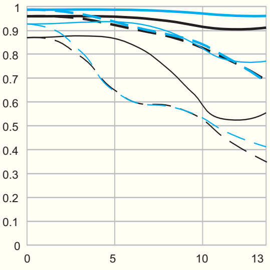
EF 100-400mm f/4.5-5.6L IS USM TELE



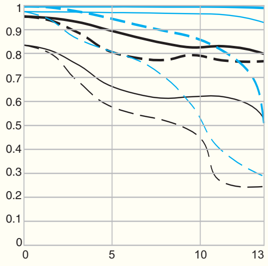
EF-S 10-22mm f/3.5-4.5 USM WIDE



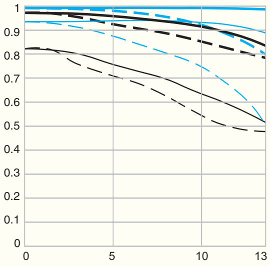
EF-S 10-22mm f/3.5-4.5 USM TELE



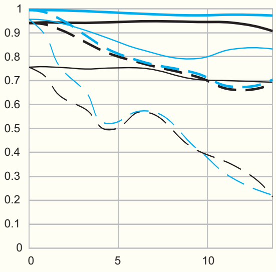
EF-S 17-55mm f/2.8 IS USM WIDE



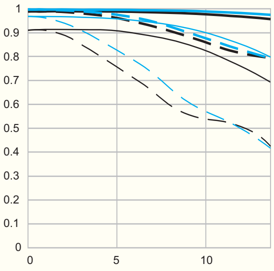
EF-S 17-55mm f/2.8 IS USM TELE



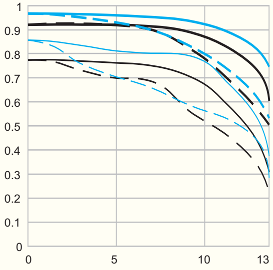
EF-S 17-85mm f/4-5.6 IS USM WIDE



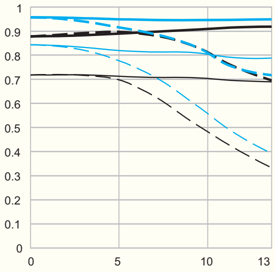
EF-S 17-85mm f/4-5.6 IS USM TELE



EF-S 18-55mm f/3.5-5.6Ⅱ USM / EF-S 18-55mm f/3.5-5.6Ⅱ WIDE

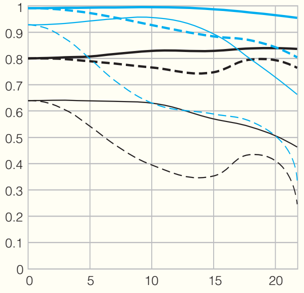


EF-S 18-55mm f/3.5-5.6Ⅱ USM / EF-S 18-55mm f/3.5-5.6Ⅱ TELE

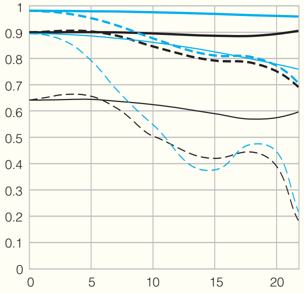


Extenders

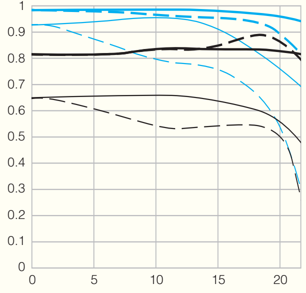
EF 1.4xⅡ



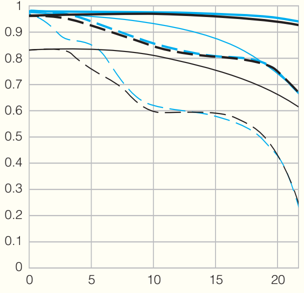
EF 70-200mm f/2.8L IS USM WIDE



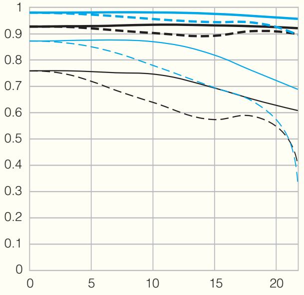
EF 70-200mm f/2.8L IS USM TELE



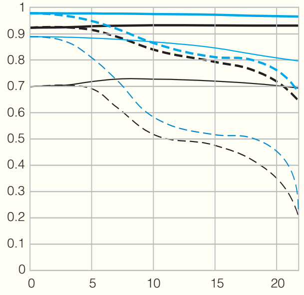
EF 70-200mm f/2.8L USM WIDE



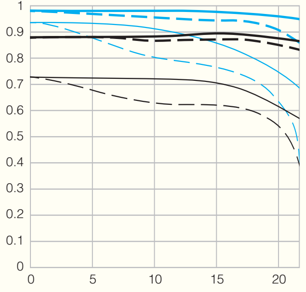
EF 70-200mm f/2.8L USM TELE



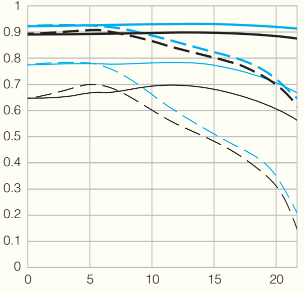
EF 70-200mm f/4 IS USM WIDE



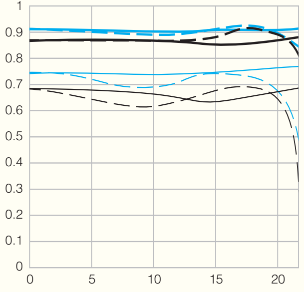
EF 70-200mm f/4 IS USM TELE



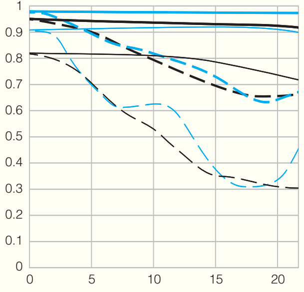
EF 70-200mm f/4L USM WIDE



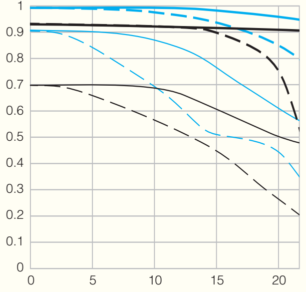
EF 70-200mm f/4L USM TELE



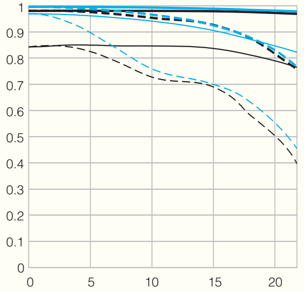
EF 100-400mm f/4.5-5.6L IS USM WIDE



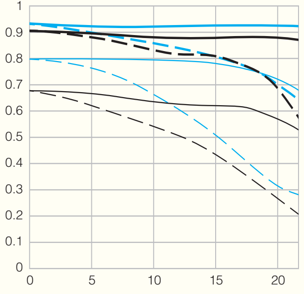
EF 100-400mm f/4.5-5.6L IS USM (—:f/16) TELE



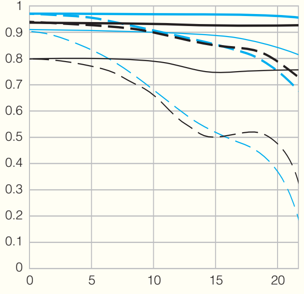
EF 135mm f/2L USM



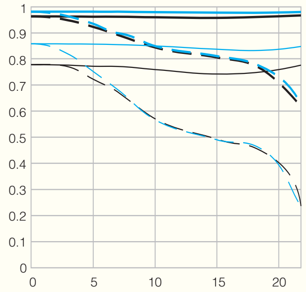
EF 180mm f/3.5L Macro USM



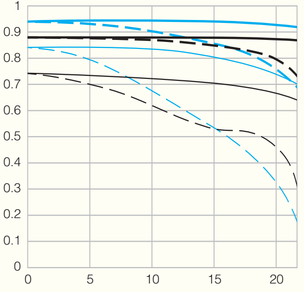
EF 200mm f/2.8L Ⅱ USM



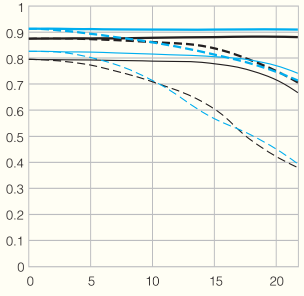
EF 300mm f/2.8L IS USM



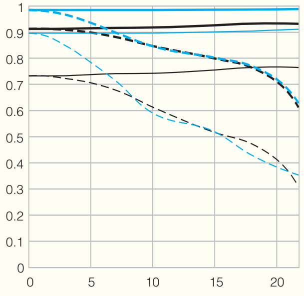
EF 300mm f/4L IS USM



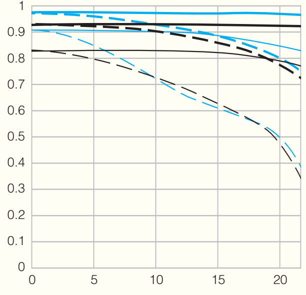
EF 400mm f/2.8L IS USM



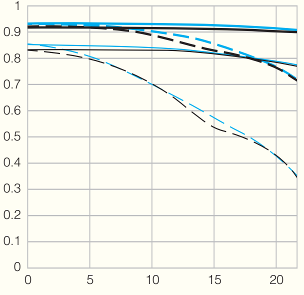
EF 400mm f/4 DO IS USM



EF 400mm f/5.6L USM (—:f/16)



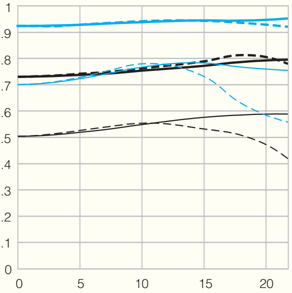
EF 500mm f/4L IS USM



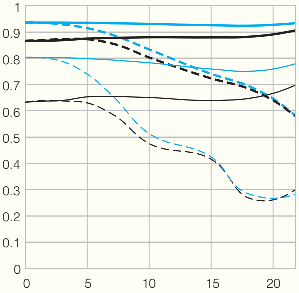
EF 600mm f/4L IS USM

EF 2xⅡ

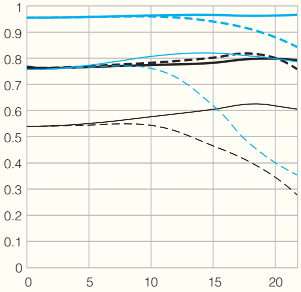
EF 70-200mm f/2.8L IS USM WIDE



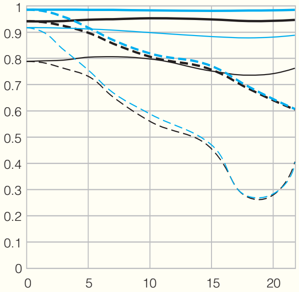
EF 70-200mm f/2.8L IS USM TELE



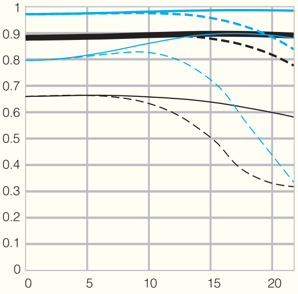
EF 70-200mm f/2.8L USM WIDE



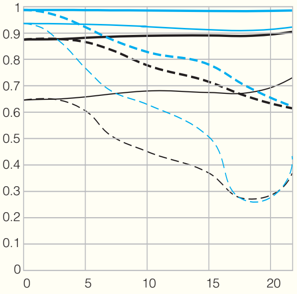
EF 70-200mm f/2.8L USM TELE



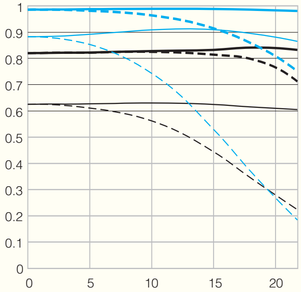
EF 70-200mm f/4 IS USM WIDE



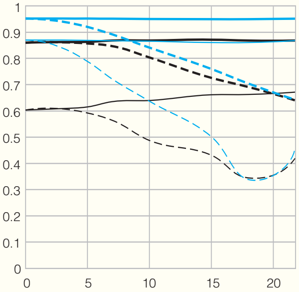
EF 70-200mm f/4 IS USM TELE



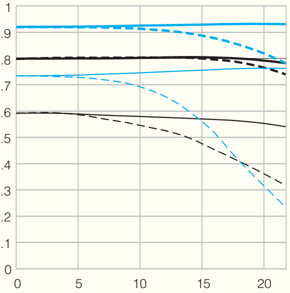
EF 70-200mm f/4L USM (—:f/16) WIDE



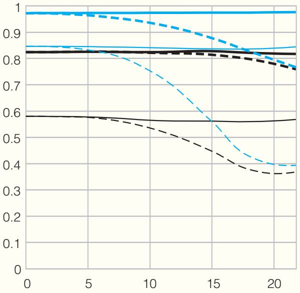
EF 70-200mm f/4L USM (—:f/16) TELE



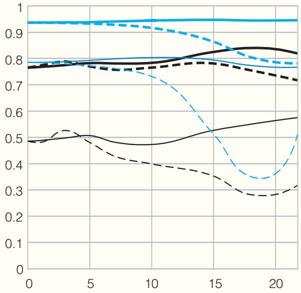
EF 100-400mm f/4.5-5.6L IS USM (—:f/22) WIDE



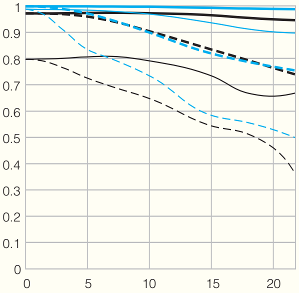
EF 100-400mm f/4.5-5.6L IS USM (—:f/22) TELE



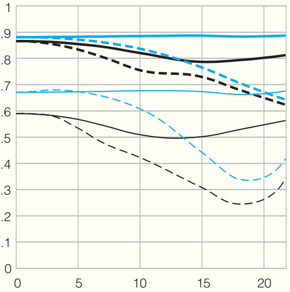
EF 135mm f/2L USM



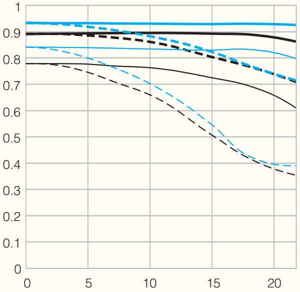
EF 180mm f/3.5L Macro USM (—:f/16)



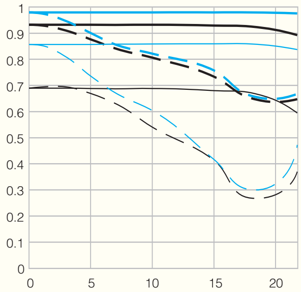
EF 200mm f/2.8L Ⅱ USM



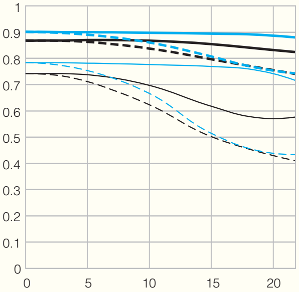
EF 300mm f/2.8L IS USM



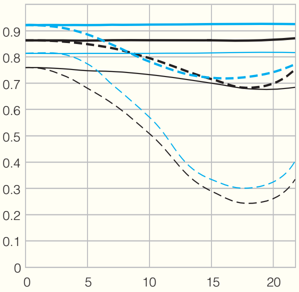
EF 300mm f/4L IS USM (—:f/16)



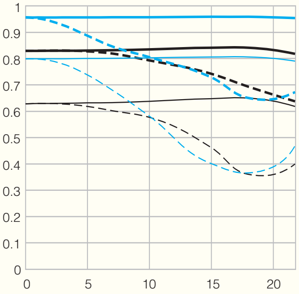
EF 400mm f/2.8L IS USM



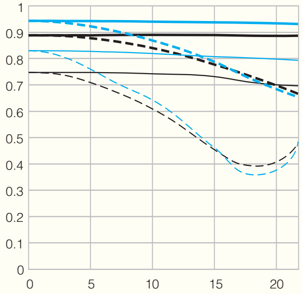
EF 400mm f/4 DO IS USM (—:f/16)



EF 400mm f/5.6L USM (—:f/22)



EF 500mm f/4L IS USM (—:f/16)



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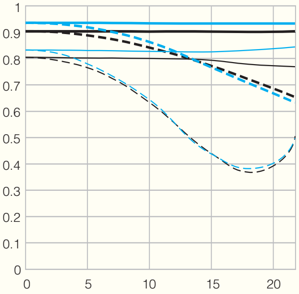

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