TV OPTICS III

The Number One Lens


MEMO
AUX2

CONTENTS

Major enclosed articles

1 Zoom Lens Functions

1.1 Principles and Structure of Scaling

A zoom lens is a lens that can be changed in focal length continuously without losing focus. The name comes from the strong visual impression that results, as if the viewer were zooming skyward in a fighter plane.

How does a zoom lens zoom in on or back from an image? Here is a simple explanation.

Anyone who has held a lens in his hand knows that changing the distance from the lens to the object changes the size of the image. The position where the image is formed also changes, so the image has to be refocused each time the lens is moved. (Fig. 1)

If two lenses are combined, by moving them in coordination it is possible to change the magnification without destroying the focus. This type of configuration, with a group of divergent and a group of convergent lenses, is used in the 35-70mm zoom lens for film photography, which has a small zoom ratio. (Fig. 2)

The zoom lenses used in television broadcasting cameras are more complex, but the basic principle remains the same—move one part of the lens system to change the size of the image, and move another part to keep it in focus.

A zoom lens therefore has at least two moving parts. The part that moves to change the image size is called the variator. The part that moves to maintain focus is called the compensator. (Fig. 3)

Figure 3 shows the optical path of a hand-held zoom lens, which has a four-part structure. The second group of lenses is the variator that changes the image size. The third group is the compensator that maintains the focus.

The first group is called the focusing group, because it is used to focus the image. The fourth group is a stationary lens group called the relay lens.

At the wide-angle end of the zoom, the variator (the divergent lens component)is brought forward, creating a retrofocus type of lens structure. At the telephoto end, the variator is moved back, so the lens structure resembles the telephoto type. (Fig. 5)

To keep the image in the same position as the two lens groups move, the lens groups must move along precise curves determined by the laws of geometric optics. The motion of the variator and compensator is controlled by the barrel cam mechanism. (Fig. 4)

The inner barrel has a linear guide groove (linear cam), and the outer barrel has a curved cam groove matching the track of the lens motion (curved cam). When the outer, curved cam barrel is turned, the variator and compensator move following the curved cam grooves.

If the correct cam curve is not followed precisely, focus will be lost during zooming. The cams are there-

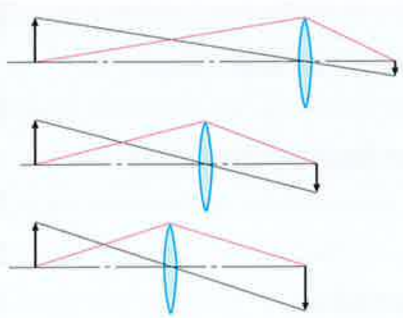


Fig.1 Changing magnification with a single lens

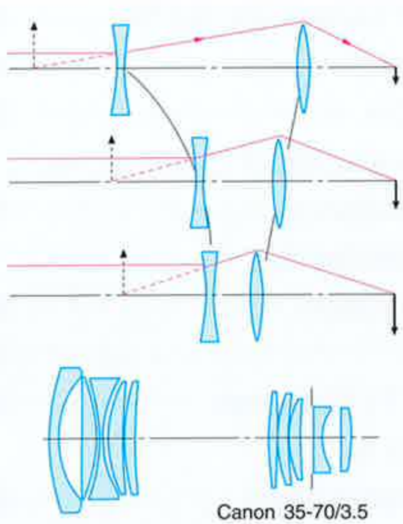


Fig.2 Zoom lens consisting of two lens groups

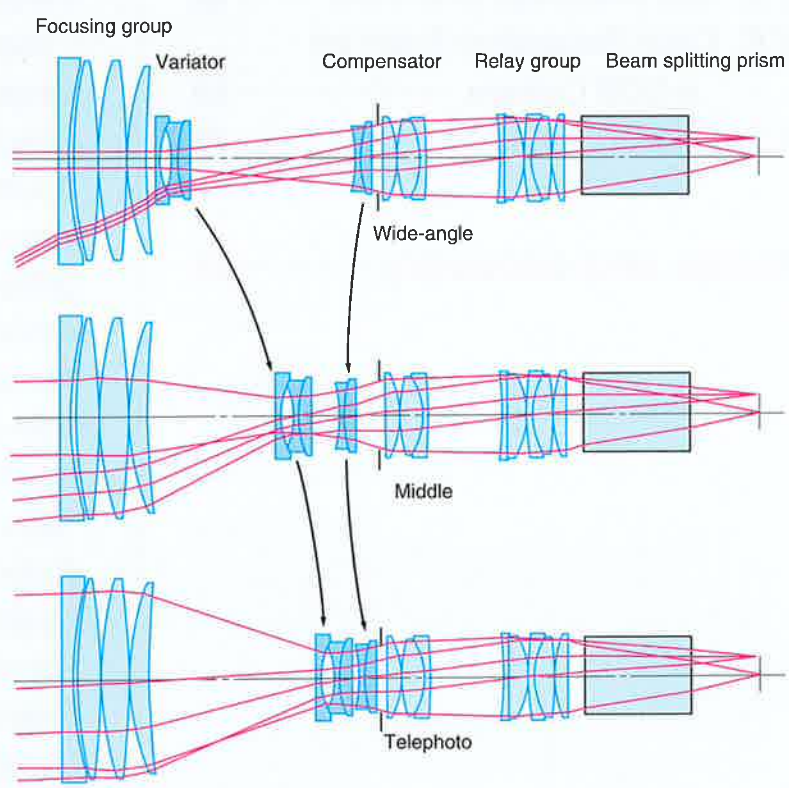


Fig.3 Optical path of hand-held zoom lens

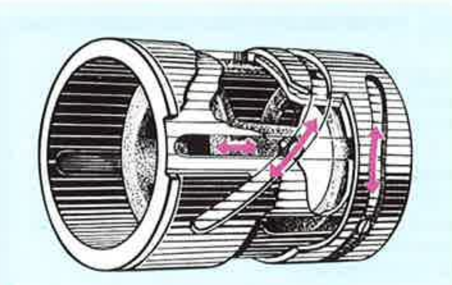


Fig 4 Barrel cam mechanism

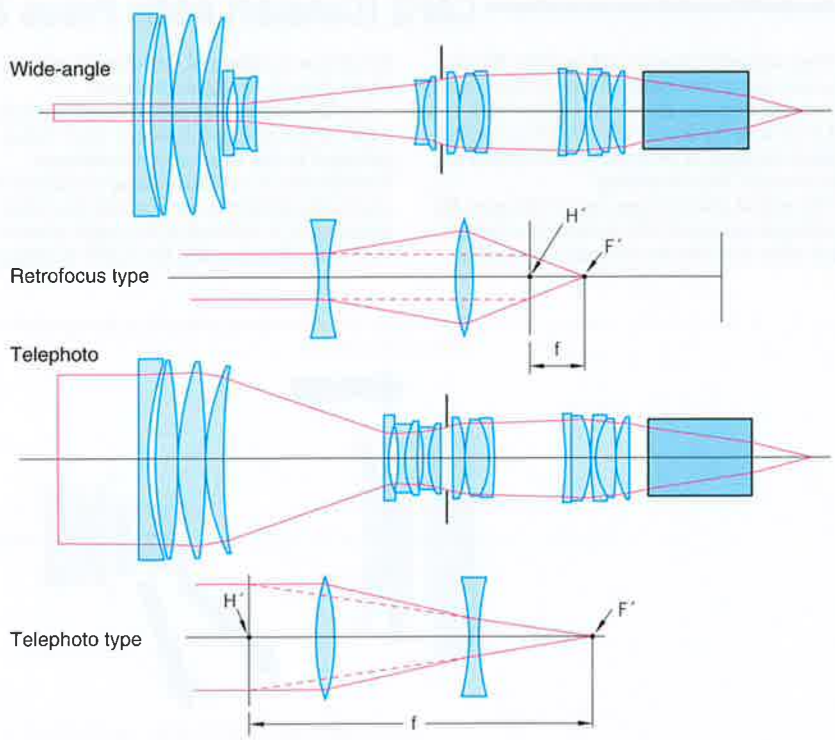


Fig.5 Lens positions at wide-angle and telephoto ends of zoom

fore machined to micron tolerances by numerically controlled machine tools.

A zoom lens must also correct optical aberration so that the image will stay sharp when zoomed. The path of the light rays through the lenses undergo complex changes during zooming. To correct aberration at all focus lengths, the aberrations caused by each of the lens groups must be minimized, and the aberrations that the individual lens groups cannot correct on their own must be carefully balanced so that one lens group corrects another. To suppress aberrations, a television zoom lens uses many more component lenses than a film camera lens.

Designing a zoom lens requires a great deal of ray tracing. Computer-aided design, using a large-scale computer, is essential. Modern zoom lenses with high zoom ratios and exacting specifications could not be produced without the foundation of theoretical aberration analysis, design know-how, and production technology.

Various Zoom Systems

The hand-held zoom lens shown as an example above has a divergent variator and a divergent compensator. The track followed by the compensator takes it forward, then back.

This zoom system was invented around 1955 by a Canon optical design engineer, Yamaji. Eminently suited for compact zoom lens applications, it has been widely used.

As another example, Fig. 6 shows a zoom lens for studio use. Here the variator is divergent, the compensator is convergent, and the compensator moves in only one direction.

A number of other zoom systems are possible. For example, there can be more than just two moving groups of lenses.

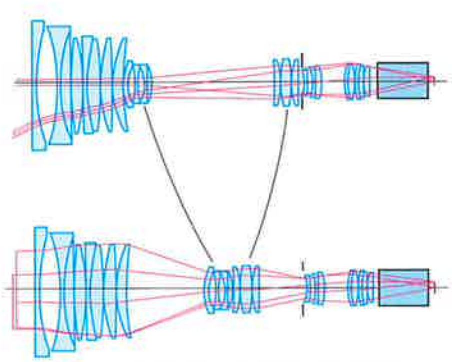


Fig.6 Optical path of studio zoom lens

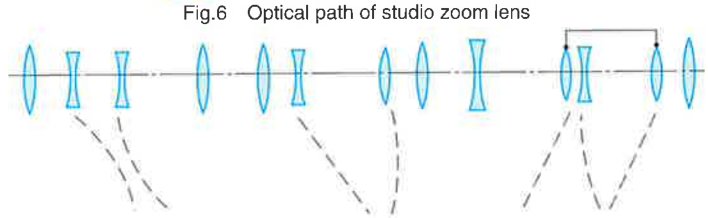


Fig.7 Other types of zoom lenses

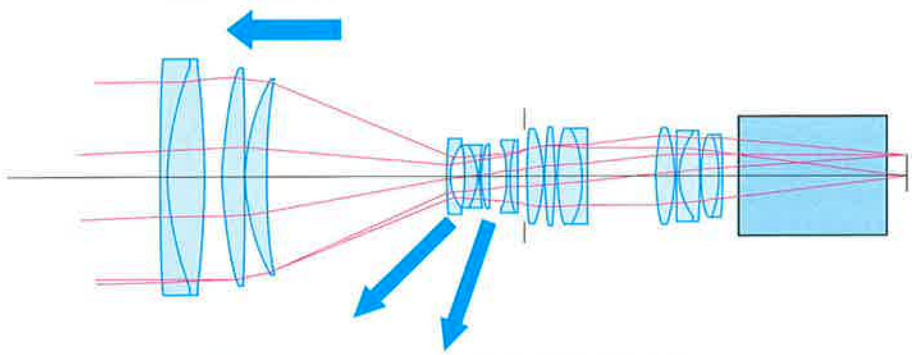
CAFS (Constant Angle Focus System)

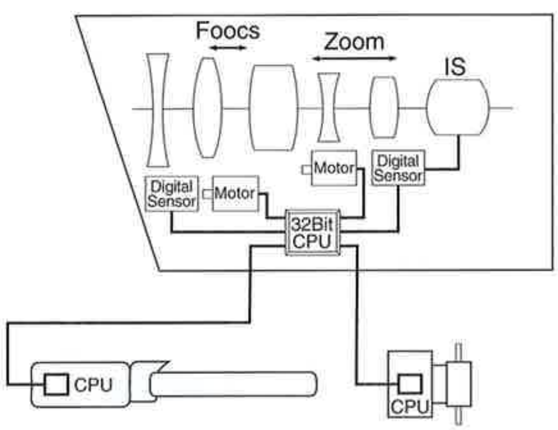
When shooting movies and so forth, the picture size may unfavorably change in the course of focusing between the objects at the back and front with the frame fixed. Such unwanted changes in angle of view with focus control are often termed "lens breathing."

This optical phenomenon occurs because the focusing group exerts the picture size change effect when it moves for focusing. Basically, the picture is enlarged (zoomed in) when a close object is brought into focus.

For TV lenses, Canon developed the technique of preventing the picture from being enlarged by the focus group movement through use of a compensating technique that zooms the picture in the opposite direction (the picture size is reduced or the angle of view is widened). This is called the CAFS (Constant Angle Focus System). Focusing on an object with this system active effectively eliminates the associated change in image size.

A 32-bit CPU mounted inside the lens body, coupled with Canon's proprietary correction technology, implements a high-precision, high-speed control over focusing and zooming when exercising normal lens operational controls during production.





1.2 Focusing System

Background of the Development of Internal Focusing Lens

In designing a zoom lens, it is very important to reduce the change in aberration during focusing as well as the change during zooming.

Conventional TV Camera zoom lenses adopted one of the two focusing methods shown in Fig. 34 on p. 23, i.e. the front group rotate-out system, and the system in which the front group is divided into convex and concave elements with rotate-out applied to the concave elements.

Further improvements in performance are required for the zoom lens as CCD cameras are widely used and HDTV technologies progress. Canon has been researching the possibility of improving the performance through the use of internal focusing with a view to putting the idea into practice.

What Is Internal Focusing?

Internal focusing for a TV zoom lens can be simply explained as the application of floating to the front group of a zoom lens.

If the front group are split into two or three subgroups and the inner subgroup is moved for focusing, the front and rear spaces of the focusing group are changed. The difference of the influences of the two spaces on the aberration is used to compensate the change in aberration during focusing. Internal focusing works only when the distribution of aberration between the fixed group and the focusing group is appropriately designed.

Characteristics of the Internal Focusing System

1. Improvement in optical performance

It is possible to improve the optical performance making use of the larger degree of freedom of aberration correction.

The performance has been improved to increase the angle of view, to reduce the change in chromatic aberration change during focusing, and to reduce distortion, etc.

2. Square hood

A square hood can be used because the barrel of the front group is stationary. In a conventional lens the hood had to be circular because the front group were designed

to rotate. The internal focusing lens can eliminate ghosting and flaring more effectively than the conventional lens by cutting unnecessary light fluxes at the square hood, and is suitable for CCD cameras.

3. Reduction of the weight of the focusing lens group

This is an important factor in terms of operation.

Focusing lens group which are lighter than those in a conventional lens can be moved quickly using little electric power, enabling smooth movement even during manual operation.

4. The use of filters

The hand held lens is used with various filter attached to front barrel. However, the filters whose properties change with rotation, such as polarizing filters, cross filters, and half ND filters, were difficult to use with a conventional lens whose front portion rotates.

These filters can be used with the internal focusing lens without any problem because the front group does not rotate, thereby enabling the filters to be used to their full effect.

5. Optical accessories

Optical accessories, such as a wide converter or tele-side converter attached to the barrel of the front group do not influence the focusing operation.

A handy mattebox can be attached directly to the barrel of the front group.

Floating System

Some single-lens reflex camera lenses with fixed focal lengths employ a focusing method called a floating system. The floating system is also called aberration correction mechanism for a short object distance. And it provides high imaging performance from infinity distance to the minimum object distance (M.O.D.) by changing some air spaces between the elements to compensate the change in aberration during focusing, as shown in Fig. 8.

When the air space between the lens elements is changed, the aberrations are affected. But if the air space is changed over some particular range, it becomes possible to mainly change only the spherical aberration, or the curvature of field, etc. The floating system is a focusing method which stabilizes the change in aberration during focusing by presenting air spaces between the lens elements appropriately and changing them in accordance with the movable amount of the focusing group.

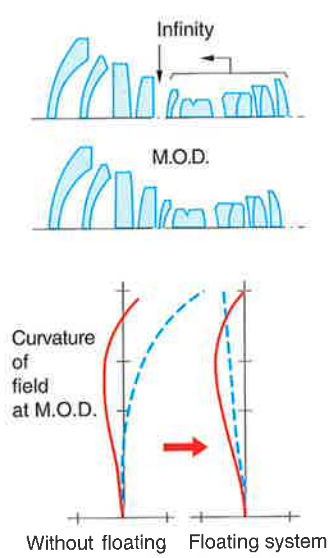


Fig.8 Floating system for a wide-angle lens

Examples of Internal Focusing System

In the internal focus system developed for wide-angle zoom lenses intended for hand-held and studio cameras, the front group (consisting of numerous lens elements required to correct optical aberrations associated with wide angle lens settings) is divided into three groups; a concave group and two convex groups, and the convex group in the middle is moved for focusing. In this case, the focusing lens group is moved toward the image plane, which is contrary to the conventional system, for focusing on the close object. Using the internal focusing system, it is possible to attain a wide-angle zoom lens without increasing its physical size. (Fig. 9)

Features of this internal focusing system are as follows:

1) Variation in optical performance due to focusing is small.
2) Breathing due to focusing action is small.

In the internal focusing system for standard and telephoto lenses, the front group is divided into two subgroups and the rear-side convex subgroup is moved out for focusing. At the optical design stage, a sharing of aberrations between the front fixed lens subgroup and the moving focusing group is carefully implemented in a manner that ensures a highly stable optical performance.

This internal focusing system achieves an optimized compatibility between high performance and compactness. Lens breathing due to zooming are somewhat larger in the standard and telephoto lenses than those of the internal focusing system for wide-angle lenses.

The focusing mechanism of the internal focusing system for hand-held cameras is shown in Fig. 11.

The Helicoid screw in which the focusing elements are mounted is connected to the external focusing ring by means of a driving pin, and rotation of the focusing ring moves the focusing elements back and forth.

Though the mechanism of the internal focusing system is more complicated than that of the conventional systems, compactness, lightweight, and high quality are fully ensured by means of computer simulations using 3-dimensional CAD.

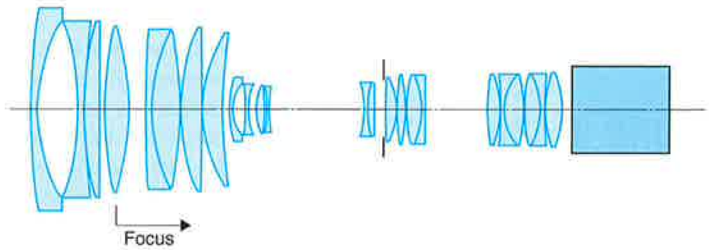


Fig.9 Three-group internal focusing for wide-angle lenses

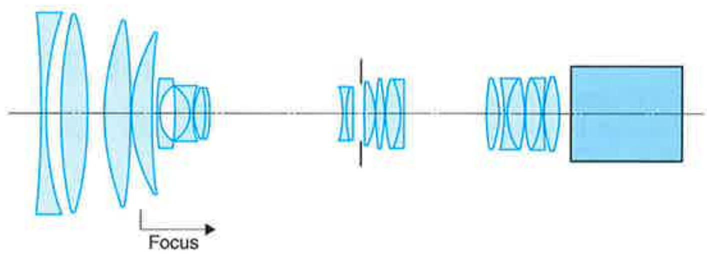


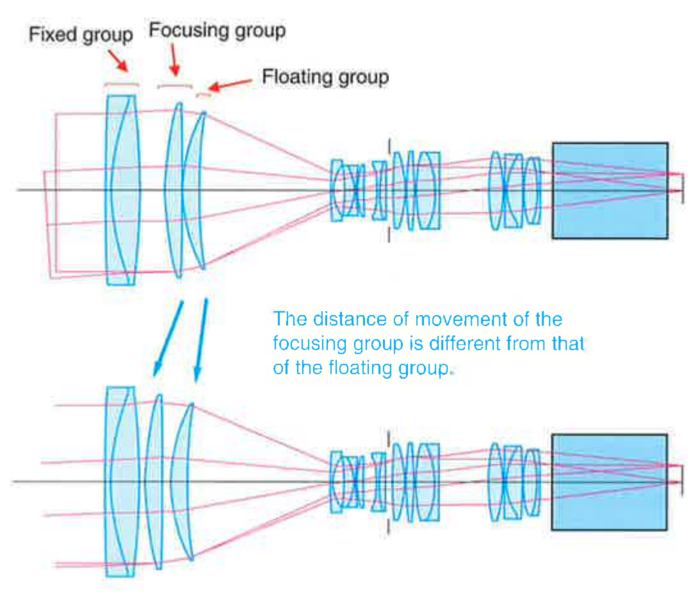
Fig.10 Two-group internal focusing system for standard and telephoto lenses

Internal Floating Focusing System

With front-lens focusing systems widely used in broadcasting zoom lenses, the longer the focal length of the telephoto end, the more the movement of the focusing group associated with changes in the subject distance is known to affect optical performance.

The floating effect of the two-lens-group internal focusing system discussed above is limited in its ability to elevate the optical performance of an HDTV system with large-aperture high-variable-ratio field zoom lenses over the entire zooming and focusing ranges.

A more recent enhancement (especially important to HDTV) to the two-lens-group internal focusing system is the so-called "internal floating focusing system," whereby a floating lens group moves independently to correct aberration variations to make two groups floating.



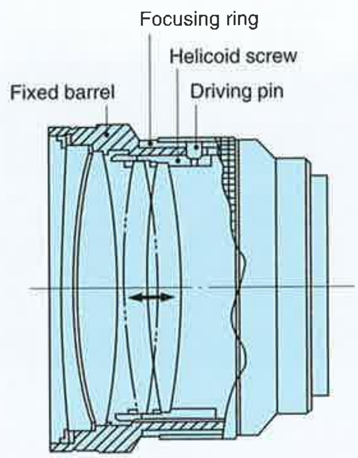


Fig.11 Internal focusing mechanism

The internal floating focusing system significantly suppresses monochromatic aberrations (spherical and comatic) and chromatic aberrations associated with changing scene subject distances caused by changing subject distances.

The internal floating focusing system enables HDTV high-magnification field zoom lenses to image powerful, high-definition pictures under a variety of shooting scenes.

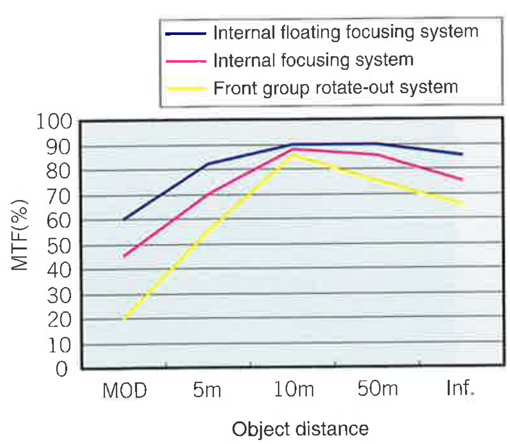


Fig.12 Performance changes with distance

Optical Vibration-proof System

The ultra-high-power lens MJ86x9.3B released by Canon in 2000 was the world's first zoom lens incorporating a lens-shift-type vibration-proof system.

According to the result of the market research conducted when developing the MJ86x9.3B, customers demanded a vibration-proof feature because they thought lenses with a focal length longer than that of the PJ70x9.5B were useless due to wind and jiggle of the platform on the top of scaffold.

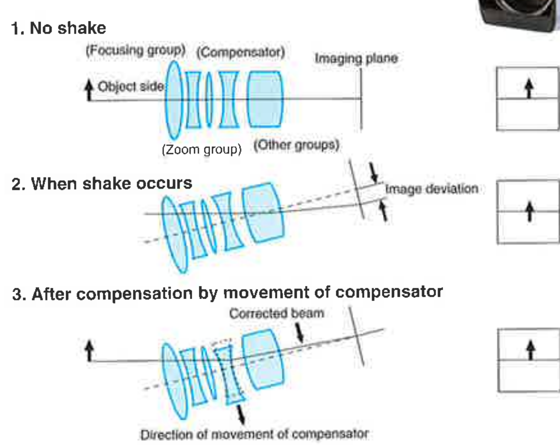
To meet the customer demand, Canon refined the well-proven vibration-proof technology used for EOS lenses in terms of performance, precision, and operation speed and designed it into the HDTV lenses.

Canon developed a combination of shake sensor and lens-shift-type compensator which is most suitable for suppressing the vibrations caused on the telephoto side of ultra-high-power HDTV lenses.

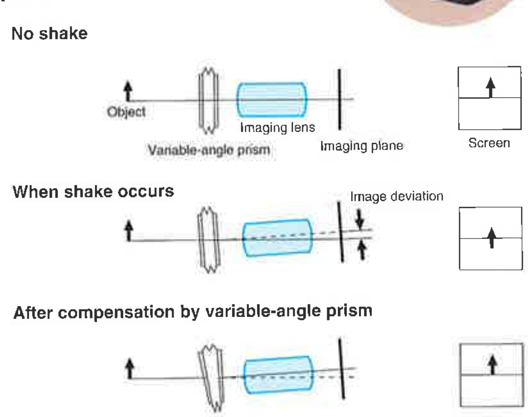
The optical compensator is packed with technical know-how that restricts the scope of lens shifting to the optical axis to suppress aberrations that could lead to flaring and single-sided blurring.

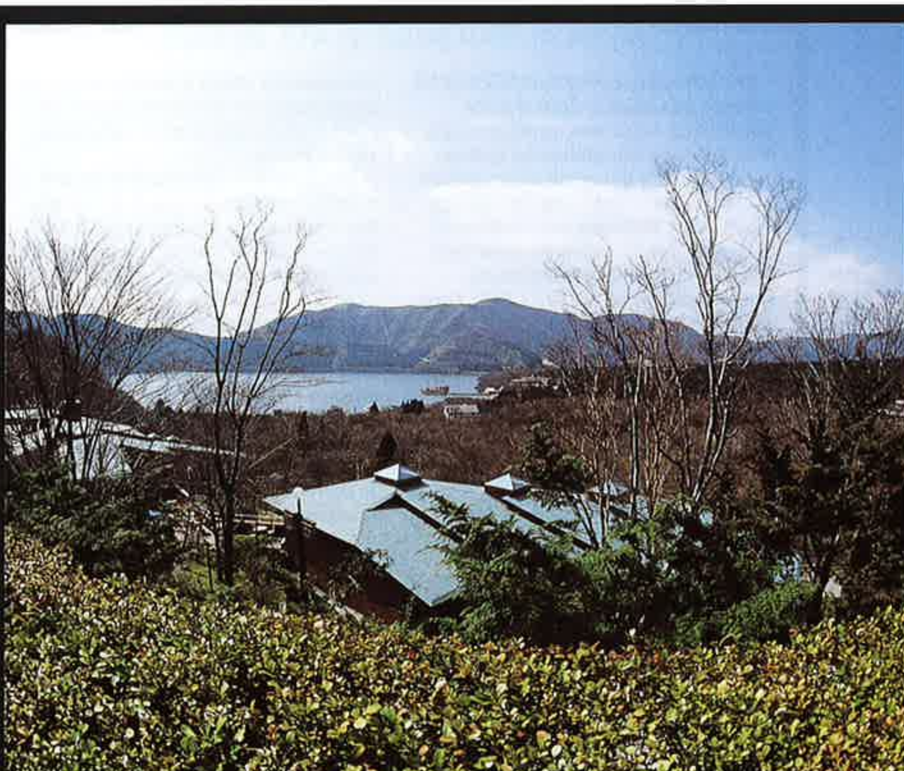
Before developing the lens-shift-type vibration-proof system, Canon succeeded in developing a vibration-proof adapter IS-20B employing a variable-apex-angle prism system. This adapter is attached at the front of the lens. The apex angle of the prism is changed to correct the optical axis deviation, preventing the image from fluctuating due to vibrations.

■Operating principle of lens-shift-type vibration-proof mechanism (MJ86x9.3B)



■Operating principle of vibration-proof adapter IS-20B





f = 4.5mm, horizontal angle of view 88.7°

f = 6mm, horizontal angle of view 72.5°

f = 125mm, horizontal angle of view 4.0°

1.3 How Zooming Changes the Angle of View

As it continuously varies its focal length, a zoom lens also changes the angle of view (the angle that the lens "sees").

Zooming enables the operator to adjust the image size and change the composition without moving the camera. This is a highly effective feature when the camera has to be used in restricted conditions.

The more wide-angle a lens is, the larger its angle of view is, and the smaller its image size is. A wide-angle lens is therefore suited for panoramic photography, and for indoor situations where it is not possible to move very far back from the subject. For this reason, wide-angle zoom lenses are used in studio cameras.

A wide-angle zoom captures both the foreground and background simultaneously, giving a powerful feeling of depth.

A telephoto zoom, because of its long focal length, gives a large image size but a narrow angle of view. Telephoto lenses are used to bring a distant subject close-up, or to get a clear picture of a subject that cannot be closely approached.

Telephoto zoom lenses with long focal lengths are used, for example, in live broadcasts of golf matches.

A telephoto zoom produces a flat image with no strong feeling of depth—the foreground and background seen to be at about the same distance. This is called the telephoto compression effect.

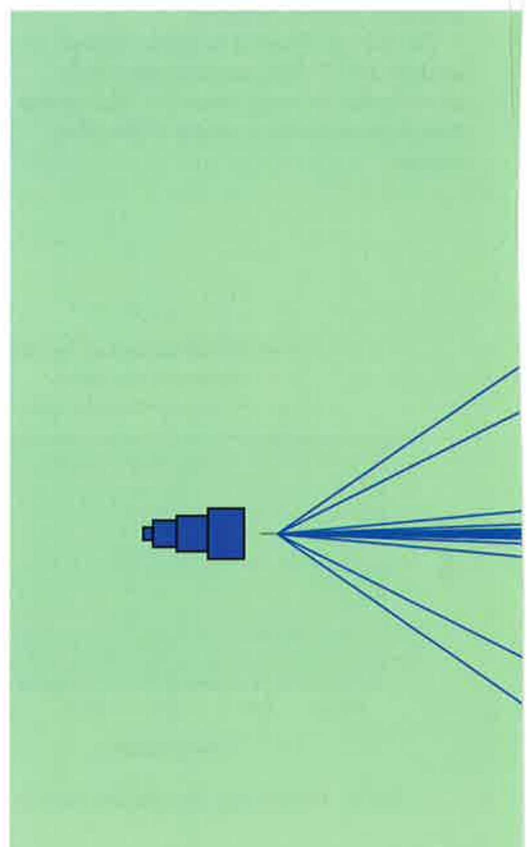


Fig.13 Changing angle of view caused by zooming (with 2/3″ lens)

f = 9mm, horizontal angle of view 52.1°

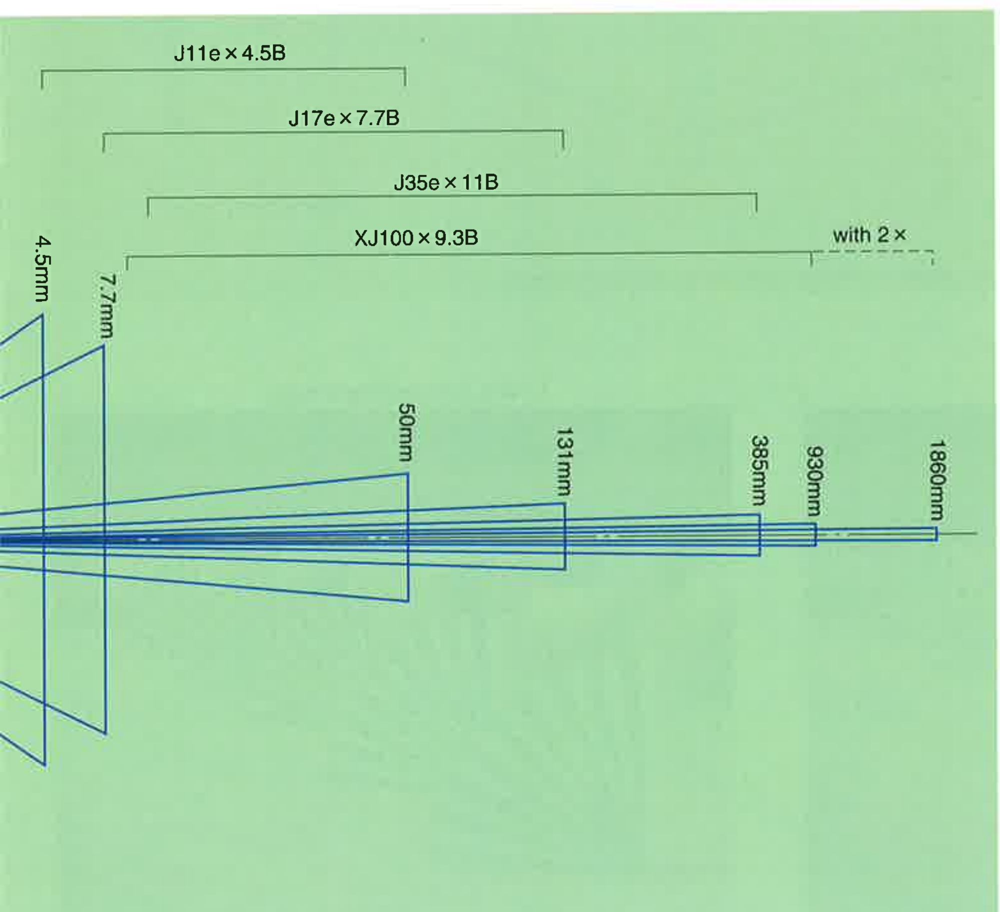
f = 25mm, horizontal angle of view 20.0°

f = 50mm, horizontal angle of view 10.1°

f = 300mm, horizontal angle of view 1.68°

f = 500mm, horizontal angle of view 1.01°

f = 930mm, horizontal angle of view 0.54°



1.4 Depth of Field

Ideally, a subject on a flat plane perpendicular to the optical axis is focused onto a flat image plane. Actually, even if the subject has depth, the image will appear to be in focus within a certain range in front and in back of the point on which the lens is focused.

If an image is out of focus by less than a certain amount (the "permissible circle of confusion"), the out-of-focus is undetectable, and the image appears sharp.

The permissible circle of confusion of a television lens can be approximately determined from the width of the raster lines. Specific values are given in the table below as a guide. Needless to say, these values are also affected by the performance of the monitor, and the conditions under which the screen is viewed.

The zone in front and back of the image plane in which the defocus is less than the permissible circle of confusion is called the depth of focus. (Fig. 14)

Image size	Permissible circle of confusion
J(2/3")	0.021mm
PH(1/2")	0.016mm
HJ(2/3")	0.005~0.010mm

The depth of field is the zone within which the subject forms an image that is within the depth of focus. Anything within the depth of field will appear as sharp as if it were in focus.

The depth of field has the following features:

1) Larger F-numbers give greater depth of field.
2) Shorter focal lengths give greater depth of field.
3) Greater subject distance gives greater depth of field.
4) Depth of field is greater behind the subject than in front.

Feature 1) means that the more the lens is stopped down, the greater the depth of field is. The lens aperture does more than just control the amount of light. It has the second important function of controlling the depth of field.

When depth-of-field effects are ex-

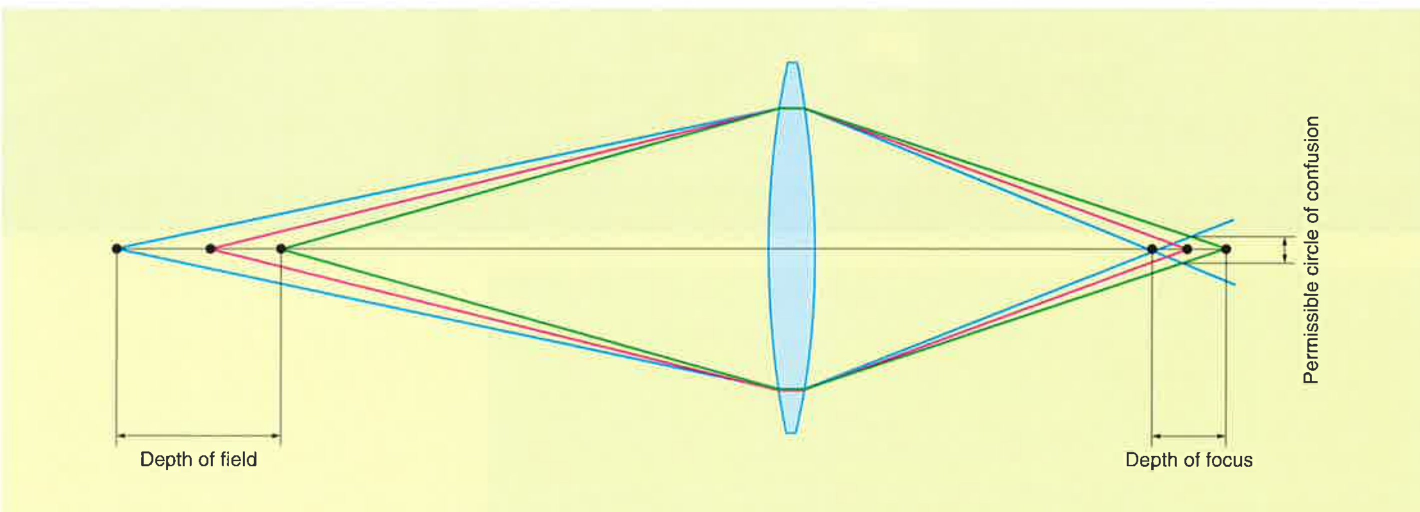
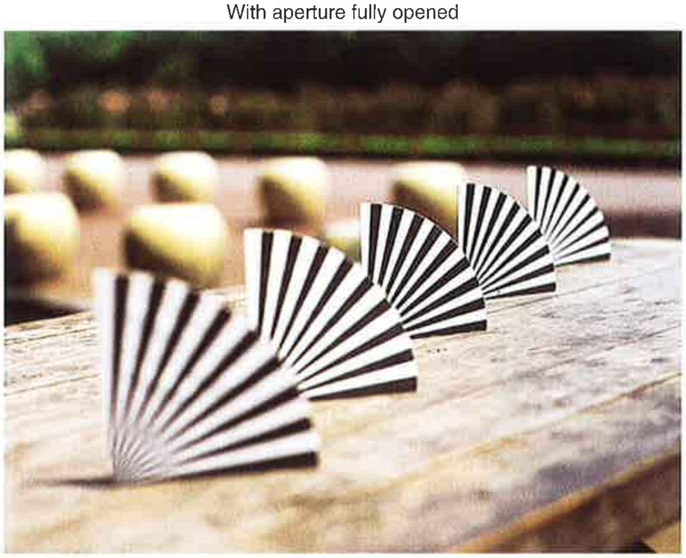
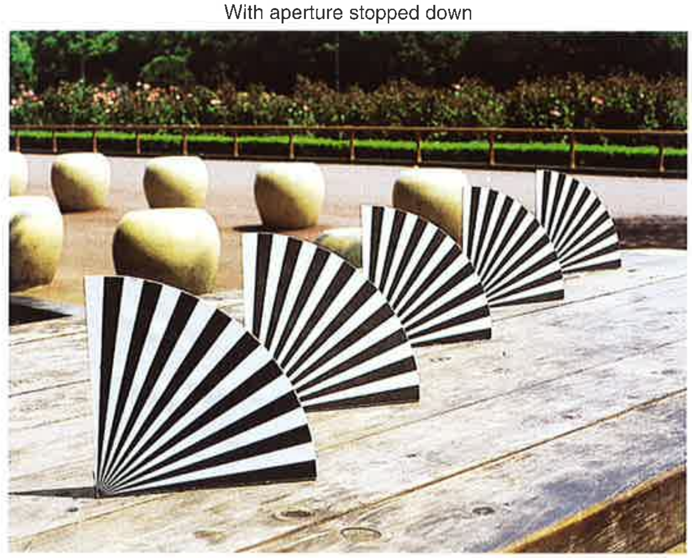


Fig.14 Relation between depth of field and depth of focus

With aperture fully opened



With aperture stopped down



ploited in shooting, the aperture cannot be adjusted to compensate for brightness. Instead, an ND filter must be used to adjust the amount of light for the desired F-number.

If the focal length is changed, the depth of field also changes, decreasing toward the telephoto direction.

Since a wide-angle lens has great depth of field, it can give both a sharp foreground and a sharp background. A telephoto lens, by throwing the background completely out of focus, can emphasize the subject it is focused on.

The Depth-of-Field Formula

When the lens is focused at a distance ℓ, the distance d_1 beyond ℓ within which a sharp image is obtained is called the far limit of depth of field, and the distance d_2 in front of ℓ within which a sharp image is obtained is called the near limit of depth of field. The depth of field is the sum of these two distances, $d_1 + d_2$.

Let the focal length of the lens be f, the F-number be F_{NO}, and the permissible circle of confusion be δ. Then (Fig. 15) we have:

$$\text{Far limit of depth of field } d_1 = \frac{\delta \cdot F_{NO} \cdot \ell^2}{f^2 - \delta \cdot F_{NO} \cdot \ell}$$

$$\text{Near limit of depth of field } d_2 = \frac{\delta \cdot F_{NO} \cdot \ell^2}{f^2 + \delta \cdot F_{NO} \cdot \ell}$$

The hyperfocal distance H is the focusing distance that brings the range from infinity to 1/2 H within the depth of field. Focusing is unnecessary within this range.

Since the hyperfocal distance is the distance at which the far limit of depth of field d_1 becomes infinite,

$$H = \frac{f^2}{\delta \cdot F_{NO}}$$

(see Fig. 16.)

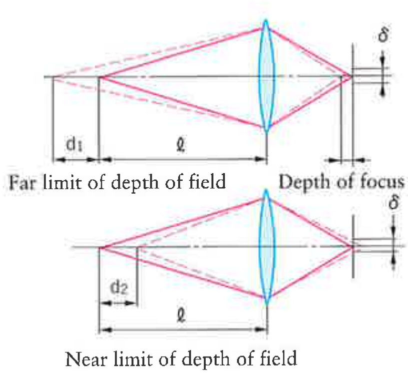


Fig.15 Far limit of depth of field and near limit of depth of field

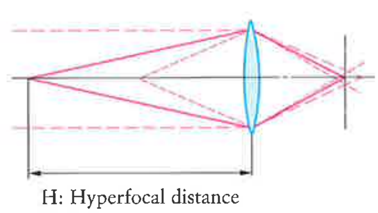


Fig.16 Hyperfocal distance

Auto-Focusing Technology

Most of today's consumer products, including home video cameras, compact cameras and single-lens reflex cameras, incorporate an autofocus (AF) capability. All AF methods implemented in such products fall into one of two broad categories: (1) the triangulation system and (2) the sharpness detection system.

(1) the triangulation system has an automated double-image matching finder, whereby the images captured through a reference field lens and a separate view field lens (that are spaced apart from each other by a specified interval known as the reference length) are shifted from each other, so that the subject distance will be determined from the angle formed by the reference lens axis and the view lens axis when the two images match.

(2) the sharpness detection system detects the amounts of blur in the images that is formed in position by the two lenses to find out the length of lens delivery that yields the sharpest image.

The AF methods may be divided into four types: active AF, passive AF and TTL AF, as well as a fourth method that uses separate ranging optics from the main lens. Active AF emits light or a sound towards the subject from the camera. The second method, Passive AF, relies on receiving light from the subject as opposed to the camera emitting light or a sound, for sharpness detection. The third method known as TTL(Through-The-Lens) AF, uses the same optical path as the main lens. Use of separate optics dedicated to ranging is vulnerable to the so-called "parallax error".

To address the need for higher accuracy in broadcasting zoom lenses, Canon unveiled TTL-AF^2 (Through The Lens/Active Auto Focus) at an NAB show in 1981 and released the YH16x7 KTS-AF as a remote-control zoom lens in 2003.

The YH16x7 KTS-AF, which combines passive and TTL AF outlined above, introduces video signals from the camera into the lenses and determines their sharpness for AF detection.

The XJ100x9.3B AF introduced at an Inter BEE in 2006 adheres to the TTL-secondary image registration phase-detection system, the mainstream in single-lens reflex cameras (still imaging), to achieve both high accuracy and a high tracking capability for HDTV.

Figure 17 schematically shows the TTL-secondary image registration phase-detection system. The secondary imaging lenses shown in the figure are a pair of lenses placed across the optical axis. They serve to focus the light transmitting through the shooting lens on different sensors as images. The states of in-focus, forward focus and rear focus are shown from top to bottom in this figure. In the in-focus state, sharp images are formed on both sensors A and B. The separation between these two images is taken as d. In the forward focus state, images appearing on the sensors are blurred, with their separation being narrower than d. In the rear focus state, blurred images are also formed on the sensors but with a wider separation than distance d. The more remote from the state of in-focus images are located (that is, the more they are defocused), the more they deviate from d. The TTL-secondary image registration phase-detection system determines the relative positional relationship between the two images to detect the amount and direction of defocusing.

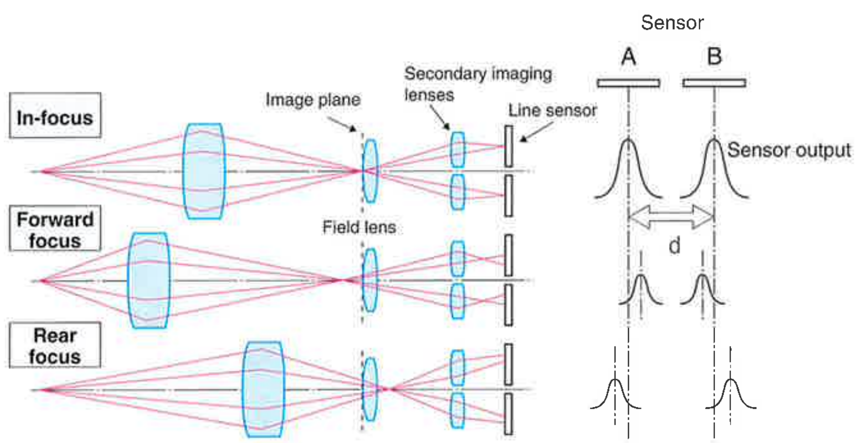


Fig.17 TTL-secondary image resistration phase-detection system

2 Fundamental Optics

Lens specifications contain a large number of figures. To interpret them, to tell whether the lens is right for a given purpose, requires some basic knowledge of optics.
This chapter explains the basic optics of a TV zoom lens.

2.1 Image Size

The first item to check in the specifications is the image size. There is no point fitting a 2/3″ lens on a 1-1/4″ camera. The image it forms is too small—the edges will be left in eclipse.
The image formed by the lens is round, not rectangular like the shape of the television screen. The range of the image is called the image circle.
In a television camera, the image pick-up device (CCD, CMOS) occupies a rectangular area inside and touching the image circle. Its size is the image size. Aberration is corrected within the range of the image circle. (Fig. 18)
Image pick-up devices varying in image size are used in modern TV cameras, and lenses are available in families to suit specific image sizes. The starting symbol of a lens name designates an image size.
The ratio of width to height of a screen is called an "aspect ratio." Normally, the conventional broadcasting scheme (SDTV) has 4:3, when compared with 16:9 for HDTV.
The five TV lens families are shown in Fig. 19, with some film lenses for comparison.

2.2 Focal Length

If parallel rays of light pass through a convex lens, they will converge to one point on the optical axis. This point is called the focal point* of the lens. The focal length of a single thin lens is indicated by the distance from the center of the lens to the focal point. (Fig. 20)
The lenses actually used in cameras are compound lenses, consisting of single lenses combined so as to correct aberrations. They function, however, like a single lens located at an imaginary point called the principal point. (Fig. 21)
The focal length is the basic parameter used to calculate the image position and magnification of a lens.

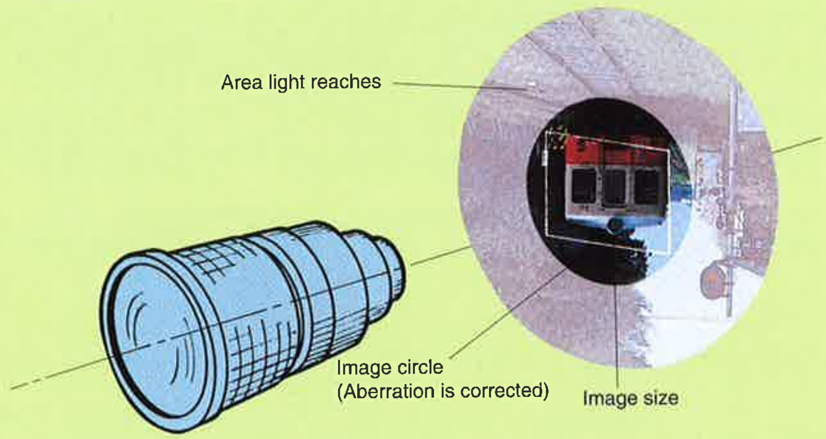


Fig.18 Image circle and image size

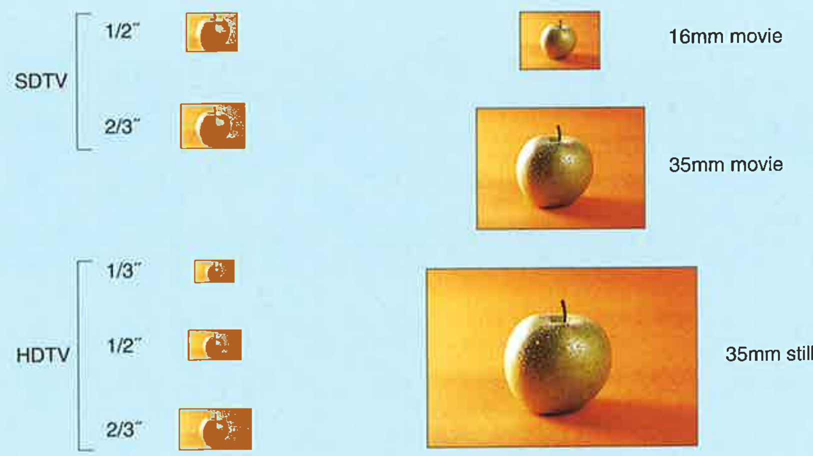


Fig.19 Image sizes for television and film (actual size)

Canon symbol		Image pick-up device size	H	V	Diagonal
SDTV	PH,H	1/2″	6.4	4.8	ϕ 8.0
	PJ,J	2/3″	8.8	6.6	ϕ 11.0
HDTV	KT	1/3″	5.23	2.94	ϕ 6.0
	KH	1/2″	7.0	3.9	ϕ 8.0
	HJ,MJ,XJ,KJ	2/3″	9.6	5.4	ϕ 11.0
Film lens	SC	16mm movie	10.3	7.5	ϕ 12.7
	K	35mm movie	22.05	16.03	ϕ 27.26
	FD,EF	35mm still	36	24	ϕ 43.3

(Unit: mm)

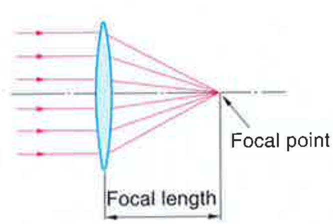


Fig.20 Focal length of a single lens

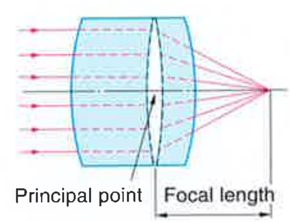


Fig.21 Focal length of a compound lens

The focal length of a television lens is important as a parameter expressing the angle of view, described in the next section.

* A lens has two focal points, one on the object side, called the primary focal point, and one on the image side, called the secondary focal point. When the term "focal point" is used alone, it means the secondary focal point.

2.3 Angle of View, Object Dimensions

The angle of view is the angular range that can be focused within the prescribed image size. Usually it is expressed as the angle from the principal point of the lens to the image plane, measured in the horizontal, vertical and diagonal directions. (Fig. 22)

If the focal length and image size are known, the angle of view w can be found as follows. (Fig. 23)

From the figure, $\tan\frac{w}{2} = \frac{y'}{2f}$, so

$$w = 2\tan^{-1}\frac{y'}{2f}$$

If the width (8.8 for a 2/3″ camera) of the image is substituted for y', this formula gives the horizontal angle of view. If the diagonal length (11 for a 2/3″ camera) of the image is substituted, the formula gives the diagonal angle of view.

The focal length and principal point of a zoom lens are changed by zooming, so it is possible to change the angle of view. (Fig. 27)

A short focal length gives a wide angle of view, and a long focal length gives a narrow angle of view, within which the image is magnified. (See Section 1.3.)

When the focusing distance is finite, instead of the angle of view, it is possible to give the actual object dimensions to fill the image format—the actual width and height that can be framed within the picture.

The Canon range calculator for TV lenses indicates the above relationships on a disk scale, so that the angle of view and object dimensions can be found without mathematical calculations. This calculator is also useful for comparing different image sizes. (Fig. 26)

The object dimensions can also be found from the chart in Fig. 29.

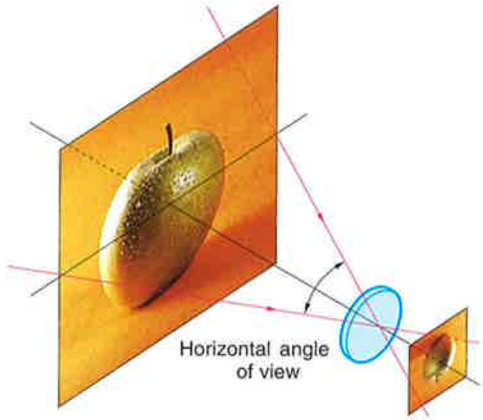


Fig.22 Angle of view

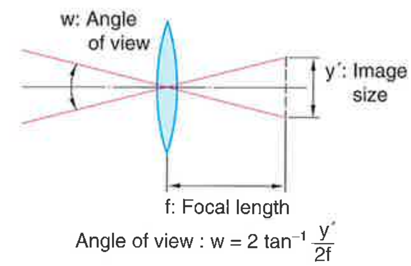


Fig.23 Calculating the angle of view

Principal Points and Image formula

A lens has two principal points, called the primary principal point and the secondary principal point. For a thin lens, both points are at the center of the lens. The plane perpendicular to the optical axis at a principal point is called a principal plane. (Fig. 24)

The principal points have the following important properties:

(1) A ray incident on the primary principal plane parallel to the optical axis will leave the secondary principal plane at the same height, traveling toward the focal point. (Ray ① in Fig. 25)

(2) An incident ray directed toward the primary principal point will leave the secondary principal point at the same angle. (Ray ② in Fig. 25)

From these properties, a graph can be constructed showing the relationship between the object and image. (Fig. 25)

The distance a from the principal point to the object and the image distance b are used in the following important formulas:

Lens equation $\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$

Magnification equation $ß = -\frac{b}{a}$

The minus sign in the magnification equation indicates that the image is inverted.

If the subject is so far away that the focal length is negligible in comparison with the object distance, the magnification can be found from the following simpler formula:

$$ß \fallingdotseq -\frac{f}{a}$$

The principal points do not have to be inside the lens system; they may be located outside it. A lens in which the secondary principal point is behind the lens is called a retrofocus lens. The retrofocus type is suited for wide-angle lens systems. If the secondary principal point is located in front of the lens, the lens is a telephoto-type lens.

The principal points of a zoom lens move when the lens is zoomed. At the wide-angle end of the zoom, the lens is of retrofocus type. At the telephoto end, it is nearly of telephoto type, as explained in Section 1.1.

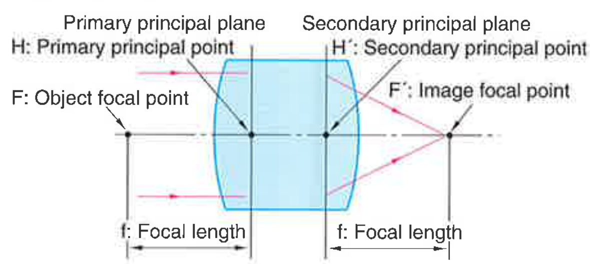


Fig.24 Cardinal points and planes of a lens

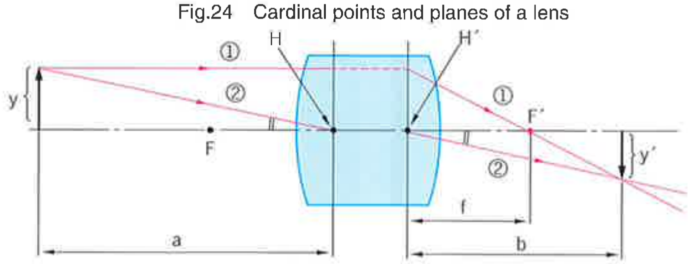


Fig.25 Relation between principal points and image

Fig.26 Canon Range Calculator for TV lenses

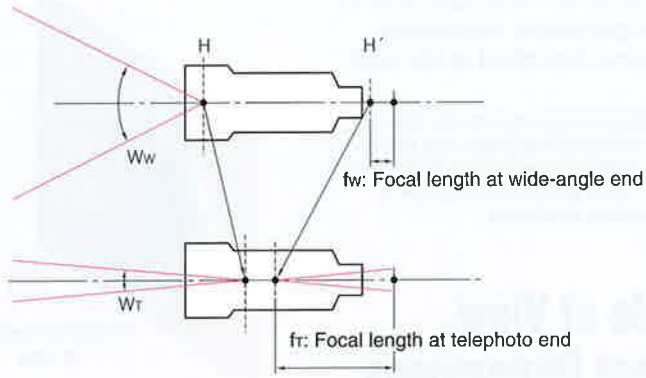


Fig.27 Changes in angle of view in a zoom lens

Calculation of the Object Dimensions

Calculating the object dimensions from the angle of view and the object distance (Fig. 28):

$$y = 2\ell \tan \frac{w}{2}$$

Calculating the object dimensions from the object distance, focal length, and image size:

$$y = y' \times \frac{\ell}{f}$$

Note:
When the focusing group of a zoom lens is moved, the focal length changes slightly. The object distance ℓ is measured from the principal point of the lens. For these reasons, the formulas above do not give precisely accurate values in close-up work.

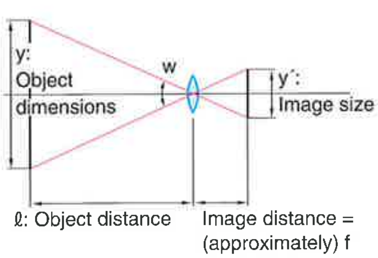


Fig.28 Calculation of object dimensions

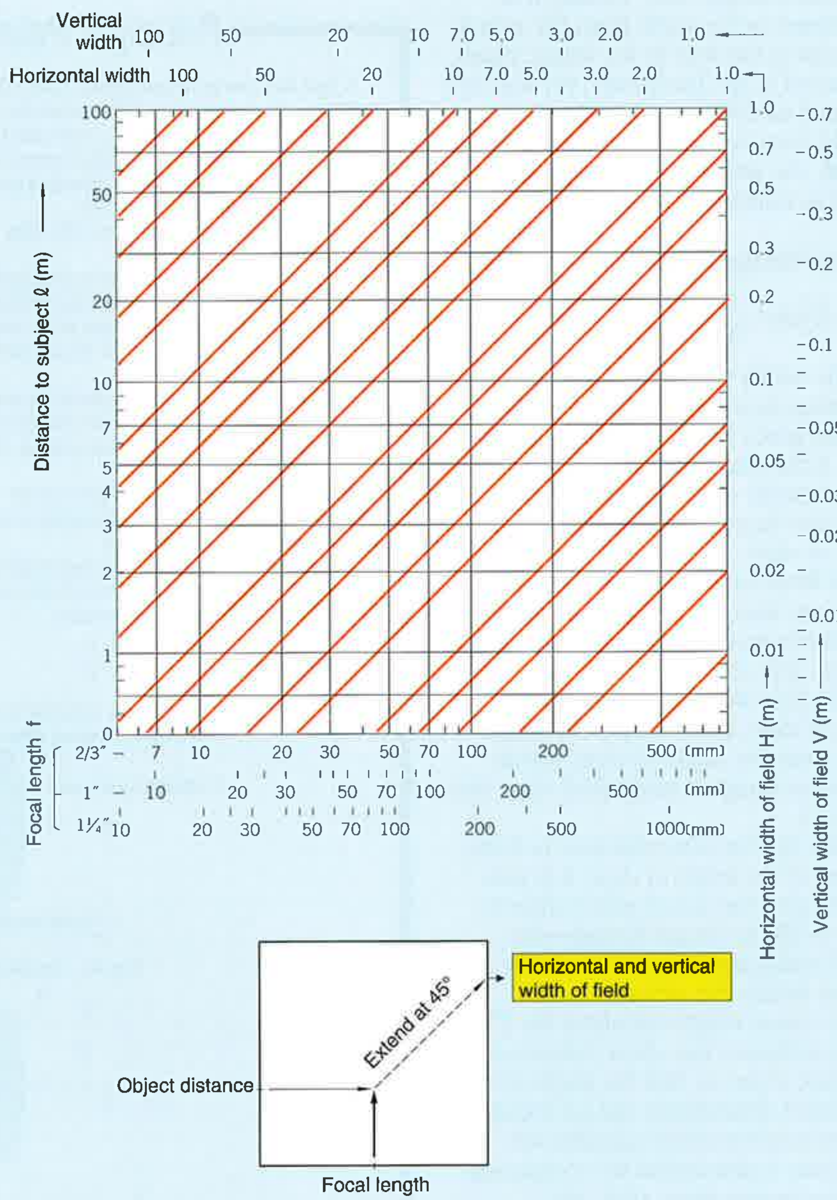


Fig.29 Width of field

2.4 Zoom Ratio

The zoom ratio is the ratio of the focal length at the telephoto end of the zoom to the focal length at the wide-angle end.

The zoom ratio indicates how much the size of the image on the monitor can be changed. If a zoom lens has a zoom ratio of 10×, the image it gives at the telephoto end will be magnified exactly 10 times as much as the image at the wide-angle end.

The larger the zoom ratio is, the more the size of the image can be changed.

It is important to select an appropriate zoom ratio. A large zoom ratio is desirable, but it also makes the lens bigger and heavier.

2.5 F-Number

An item of equal importance with the focal length is the F-number, which indicates the brightness of the image formed by a lens. A smaller F-number means a brighter image.

As was explained in Section 1, the F-number is closely related to the depth of field.

If f is the focal length of a lens and D is its effective aperture, then the F-number F_{NO} is:

$$F_{NO} = \frac{f}{D}$$

For a given focal length, the larger the aperture of the lens is, the smaller its F-number is. (Fig. 30)

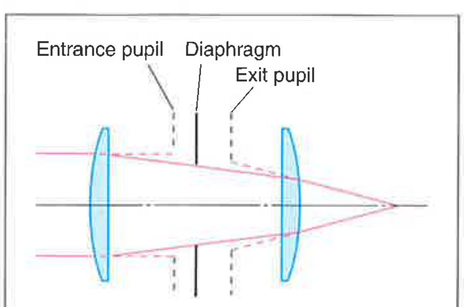


Fig.32 Entrance pupil

The stop ring of the lens is marked with a series of numbers with a ratio of $\sqrt{2}$: 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22. The amount of light entering the lens is proportional to the cross-sectional area of the flux (to the square of its diameter), so the brightness of the image is in inverse proportion to the square of the F-number. Each time the ring is turned one number up the F scale, the brightness is decreased by half. (Fig. 31)

The effective aperture D of a real lens is not its actual diameter, but the diameter of the image of the diaphragm seen from in front of the lens (called the entrance pupil*). The position of the entrance pupil of a zoom lens changes when the lens is zoomed, and its diameter also changes in proportion to the focal length; so that it is small at the wide-angle end and large at the telephoto end. This property is the cause of the F drop, which is described next.

* The image of the diaphragm formed by the part of the lens in front of it is called the entrance pupil. (Fig. 32)

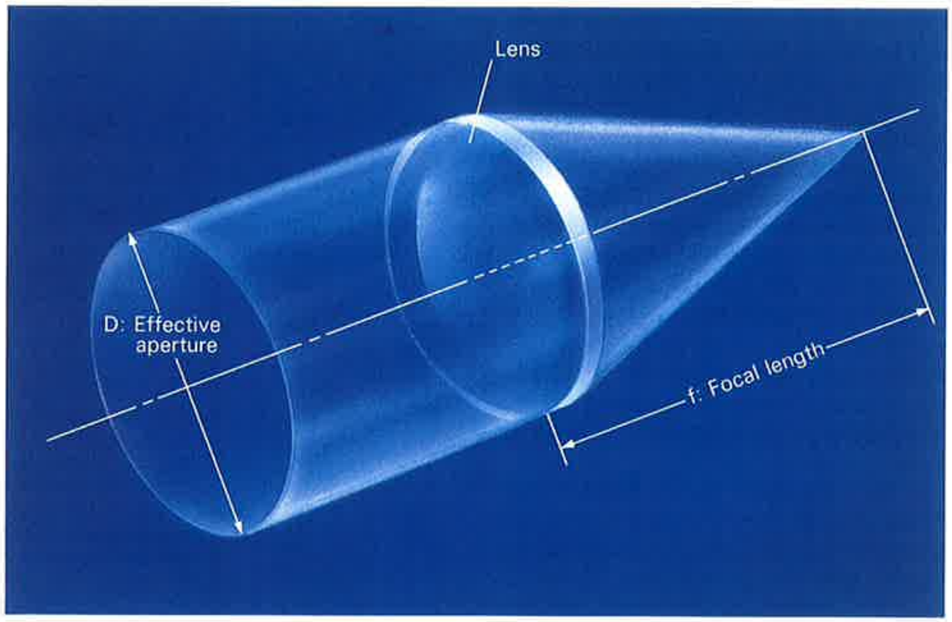


Fig.30 Definition of F-number

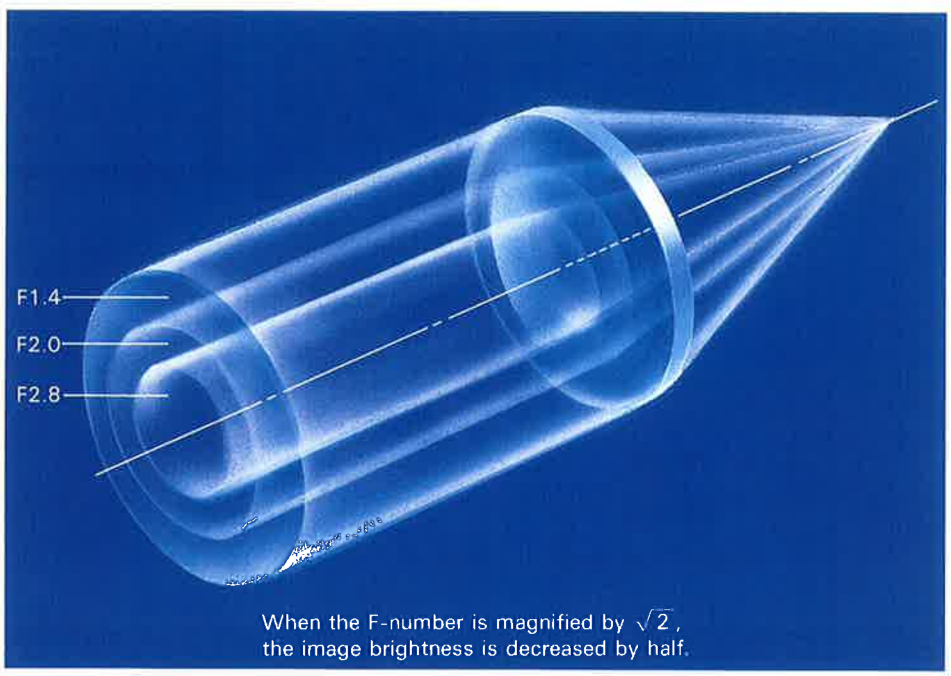


Fig.31 Relation between aperture and F-number

F Drop

If you have zoomed with a zoom lens open to full aperture, you may have noted a drop in video level at the telephoto end. This is called the F drop. (Fig. 33)

The entrance pupil of a zoom lens changes in diameter as the focal length is changed. As you zoom toward the telephoto end, the entrance pupil gradually enlarges. When the entrance pupil diameter is equal to the diameter of the focusing lens group, it cannot become any larger, so the F-number drops. That is the reason for the F drop.

To eliminate F drop completely, the focusing lens group has to be larger than the entrance pupil at the telephoto end of the zoom. It has to be at least equal to the focal length at the telephoto end divided by the F-number.

To reduce the size and weight of a zoom lens, it is common to allow a certain amount of F drop. For better composition effect, however, in some studio zoom lenses the focusing group is made large enough that no F drop occurs.

F drop is a major determinant of the value of zoom lenses used in live on-site sports broadcasts, which require a long focal length and must frequently contend with twilight or inadequate artificial illumination.

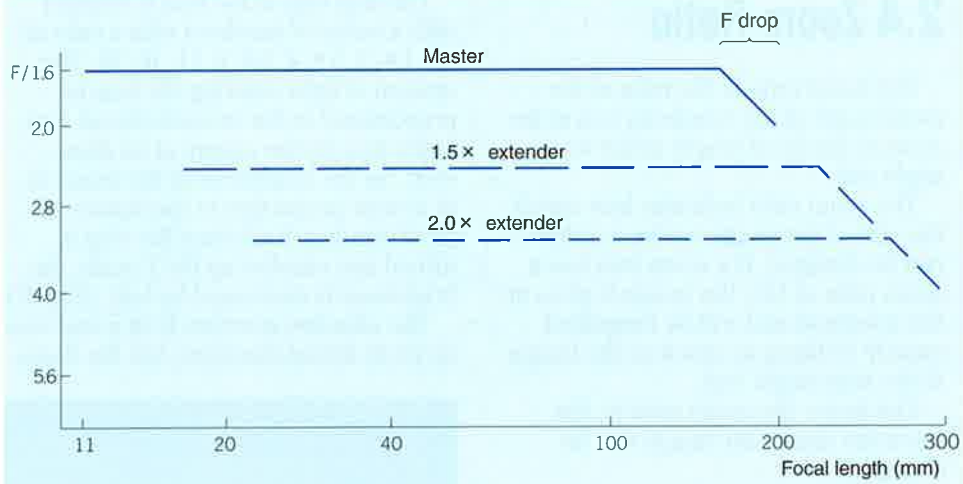


Fig.33 F drop of a zoom lens

T-Number

As many people know, movie camera lenses are rated by a T-number instead of an F-number.

The F-number expresses the speed of the lens on the assumption that lens transmits 100% of the incident light. In reality, different lenses have different transmittance, so two lenses with the same F-number may actually have different speed.

The T-number solves this problem by taking both the diaphragm diameter and transmittance into account. The T-number and F-number are related by the following formula:

$$\text{T-number} = \frac{\text{F-number}}{\sqrt{\text{Transmittance (100\%)}}} \times 10$$

Two lenses with the same T-number will always give the same image brightness.

2.6 Minimum Object Distance (M.O.D.)

The minimum object distance (M.O.D.) is the closest distance to which the subject can be approached, measured from the vertex of the lens (the front-most surface of the focusing group).

Because of the restricted space in a studio, studio camera lenses have to have a short M.O.D.

If you need to get closer than the M.O.D., a macrophoto mechamism enables you to do so. If your lens does not have a macro feature, a close-up lens can be used.

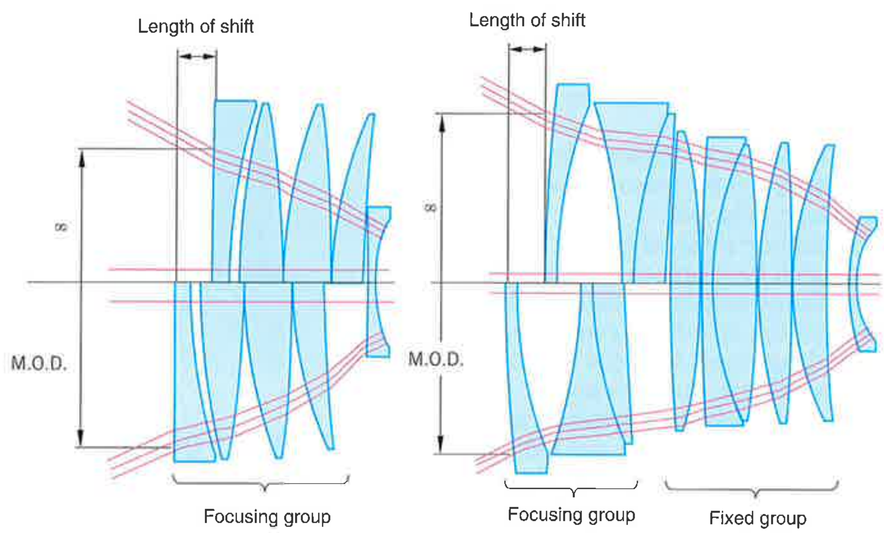


Fig.34 Focusing system of TV lens

Macro

In a macro zoom lens, lens groups other than the focusing group are shifted to focus on objects closer than the M.O.D.

As the object moves closer, the image point moves farther back from the lens. Macro shooting with a zoom lens is possible if one of the lens groups can be moved to return the image point to the normal image position.

The range where macro shooting is possible varies with the focal distance of the zoom lens. Generally, the distance that allows macro shooting becomes shorter as the focal distance of the zoom lens becomes shorter.

Macro focusing can also be used to throw the image out of focus at the wide-angle end where the image cannot be defocused by normal focusing.

Besides the focusing group, several lens groups can be shifted for macro focusing, such as the relay group, variator or compensator.

In Fig. 35, the rear relay group is shifted for the macro effect.

If the lens does not have macro focusing but does have a flange-back adjustment, a similar effect can be achieved by using the flange-back adjustment. Flange-back readjustment is then required when the lens returns from macro to normal shooting, however.

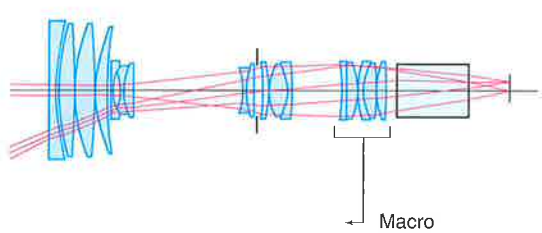


Fig.35 Macro focusing of TV lens

2.7 Flange-Back and Back Focal Length

Flange-back is one of the key factors in lens selection.

Flange-back is the distance from the flange surface of the lens mount to the image plane. (Fig. 36)

This distance must, of course, precisely match the distance from the camera flange surface to the surface of the image pick-up tube. A camera has a specific flange-back so a lens with the same flange-back must be chosen.

The flange-back of a television camera lens is converted in air and indicated as, for example, 48mm in air, or 58mm in air. This is to give a fixed value, independent of the type and thickness of glass in the beam-splitting prism, filters, and CCD face plates inserted in the optical path. The actual length is converted to what the length would be in air if these components were removed.

If a glass block of thickness d (mm) and refractive index n is inserted behind the lens, the flange-back is affected according to the formula:

$$\text{F.B.(in air)} = \text{F.B.(actual)} - \left(1 - \frac{1}{n}\right) \times d$$

Ordinarily you will never have to worry about the actual flange-back. All you need to work with is the flange-back in air.

A television zoom lens is shipped setting to a specific flange-back, but has a flange-back adjustment mechanism with which the flange-back can be changed up to about ±0.5mm by moving part of the lens.

Back focal length is the distance from the back-most surface of the lens to the image plane. Like flange-back it is usually indicated by the converted in-air value. It is designed to avoid contact with the camera's filter and dust-protection glass.

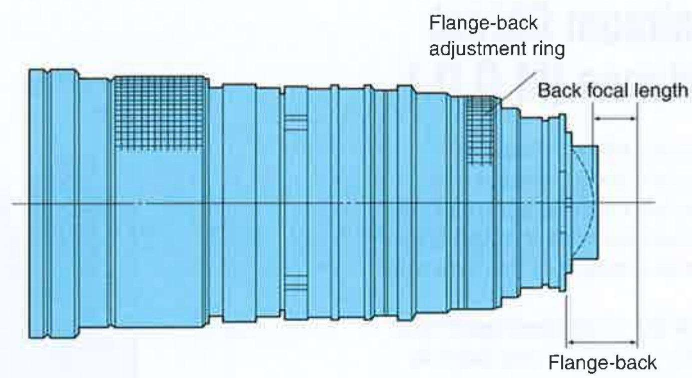


Fig.36 Flange-back and back focal length

Optical Path Elongation Caused by a Glass Block

A coin under water appears to be "floating" higher than its actual position. This is because apparent length is shorter in a medium with a higher refractive index. (Fig. 37)

If d is the true depth of the coin and n is the refractive index of water, then the apparent depth of the coin is:

$$\text{Apparent depth} = \frac{d}{n}$$

A glass block has the same effect. If its thickness is d and its refractive index is n, it is equivalent to a length of d/n in air. (Fig. 38)

If a glass block of thickness d is inserted in the optical path, the total length is increased by $(1 - \frac{1}{n}) \times d$. If the refractive index of the glass is 1.5, the elongation is 1/3 the thickness d of the block.

As will be seen in the Section 2.8, the glass block also affects aberrations.

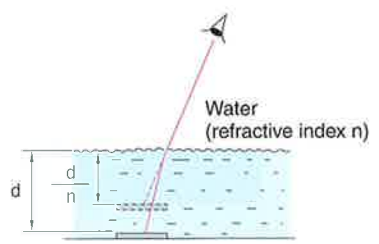


Fig.37 Coin appearing to float in mid-water

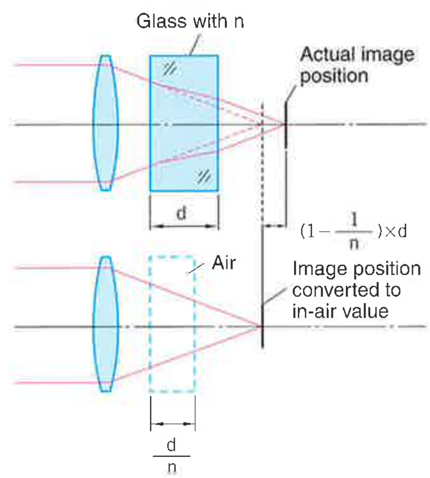


Fig.38 Lengthening of optical path by glass block

2.8 Glass Compensation

A television camera contains a beam-splitting prism, filters, and other glass blocks. Its lens has to be corrected so that it will deliver optimum performance when these glass blocks are inserted.

Different television cameras have different beam-splitting prisms, so the lens glass compensation has to be matched to the type of camera.

At present, the glass compensation of 2/3″ HDTV cameras is nearly standardized, but 2/3″ SDTV cameras still use a wide variety of beam-splitting prisms.

When the glass blocks inserted behind the lens differ from the designed glass compensation, the main effects are increased spherical aberration and longitudinal chromatic aberration.

When the glass thickness differs

Over-correction of spherical aberration occurs at the entrance surface of the glass blocks inserted in a convergent optical path, and under-correction of spherical aberration occurs at the exit surfaces. The further the rays are from the optical axis, the greater the spherical aberration is, so the glass block as a whole gives rise to an over-correction.

The lens is therefore designed to leave spherical aberration under-corrected, to cancel out the over-correction of the glass block. (Fig. 39)

When the thickness of the glass block differs from the design value, this balance is lost, spherical aberration occurs, and the modulation transfer function (MTF—see Section 2.11) degrades at high frequencies.

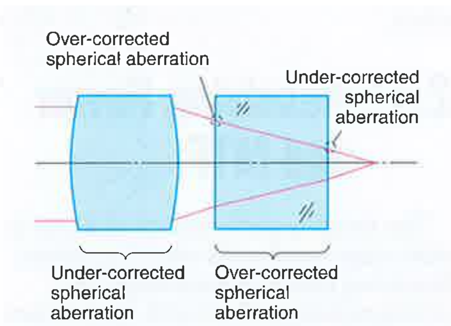


Fig.39 Correction of spherical aberration taking a glass block into account

With an SDTV lens, differences in the compensation thickness of 2 to 3mm can be ignored, but as the F-number becomes smaller, the miscompensation effect becomes larger. With an HDTV lens, the difference must be kept within 1mm.

Since the miscompensation effect lessens as the F-number increases, if the lens is stopped down to F5.6 or above, the effect almost completely disappears. (Fig. 40)

The letters and numbers at the end of the lens designation indicate the glass compensation type. If the designation is J17e × 7.7B4, for example, the letter B indicates that the lens is glass-compensated, and the number that follows indicates the type of compensation.

J17e × 7.7 B 4
- B: Glass compensated (beam-splitting prism type)
- 4: Glass compensation type; depends on the camera

Lenses with different glass compensations have the same zoom components, but different relay lenses to match the glass compensation aberration.

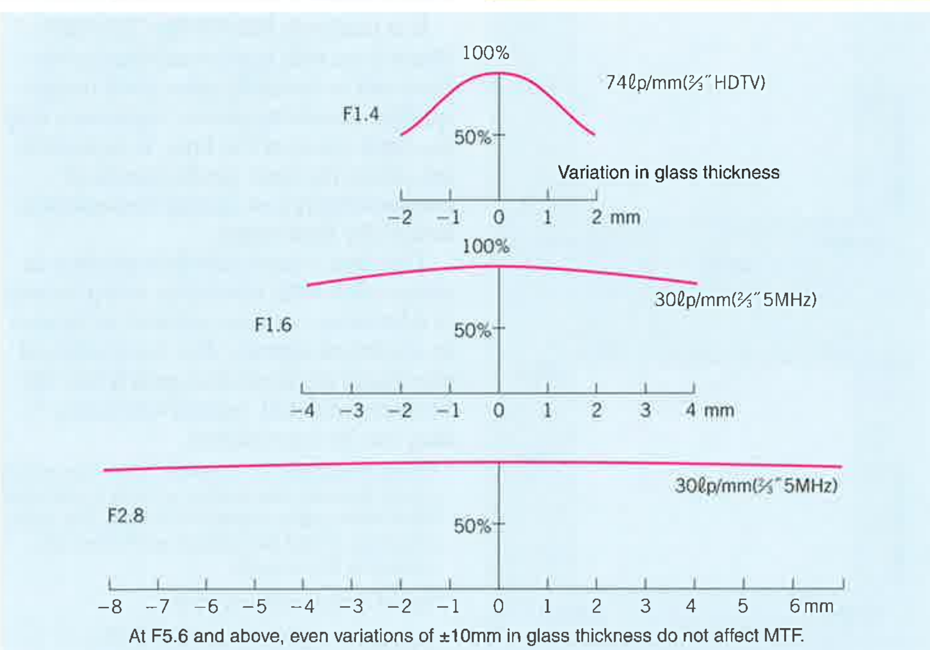


Fig.40 Variation in MTF caused by departure of glass thickness from design correction value

2.9 Exit Pupil

Unlike a photographic lens, a television camera lens is coupled to a color-separating optical system behind it. The position of the exit pupil is therefore particularly important.

The exit pupil refers to the (virtual) image of the diaphragm formed by the lenses behind the diaphragm.

The position of the exit pupil is usually expressed as its distance from the image plane. (Fig. 41)

In a television lens, the lens group (the relay lenses) behind the diaphragm does not move, so the exit pupil position remains constant, and is not affected by zooming. The apparent position of the exit pupil does move, however, due to vignetting, which will be discussed in Section 2.10.

The rays that exit from the lens toward the image appear to exit from the exit pupil.

A ray that travels from the center of the exit pupil (the point on the optical axis) to any point on the image plane is called a principal ray. As the diaphragm is stopped down, the exit pupil becomes proportionately smaller, until finally only the principal rays are left.

When the exit pupil is at infinity (in which case it is said to be telecentric), all the principal rays are parallel to the optical axis.

The color separation prism in a television camera has a dichroic coating. The spectral characteristics of this coating differ depending on the angle of incidence; the smaller the angle between the principal rays and the optical axis, the better these characteristics are. This point will be covered in more detail when we come to prisms.

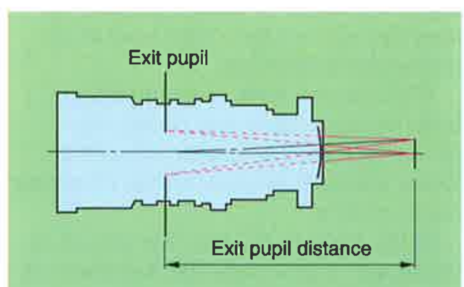


Fig.41 Exit pupil and exit pupil distance

2.10 Light Distribution

The F-number, which expresses the speed of a lens, indicates the amount of light collected at the center of the image. The off-axis points of the image do not necessarily receive this amount of light.

Light distribution is expressed in form of the ratio between the brightness at the center of the image and off-axis point.

Less light reaches the edges of the image than the center for two reasons: vignetting, and the cosine 4th-power law. The marginal light density is the product of these two factors.

If you open the stop and peer into the lens from the center, the entrance pupil will look round, but if you peer in at an angle the entrance pupil will appear to have an oval shape, because the lens barrel eclipses part of the marginal light. This is called vignetting.

The area ratio of the peripheral to the center incident pupil is called an "aperture efficiency."

As the aperture is stopped down, the oval becomes closer to a circle, even when observed at an angle. Stopping down the lens therefore reduces the effect of vignetting, and improves the light distribution. (Fig. 42)

Vignetting can be eliminated by increasing the diameter of the lens. In practice, a certain amount of vignetting is allowed so that the lens can be reasonably compact.

The second factor, the cosine 4th-power law, is present even in a lens that has no vignetting. The light reaching the margin of the image decreases as the 4th power of the cosine of the angle of view. This effect therefore increases as you zoom toward the wide-angle direction.

On the wide-angle side, the diameter of the entrance pupil changes according to the angle of view, reducing the aperture efficiency to take care of the cosine 4th-power law.

With a zoom lens, zooming affects both the vignetting and cosine 4th-power factors. The cosine 4th-power factor changes because of the changing angle of view.

At the wide-angle end, the center of the image is generally flat, but there is a rapid fall-off at the corners (due to both vignetting and the cosine 4th-power law.) At the telephoto end, there is a gentle drop-off from the center toward the margin (mainly due to vignetting). (Fig. 43)

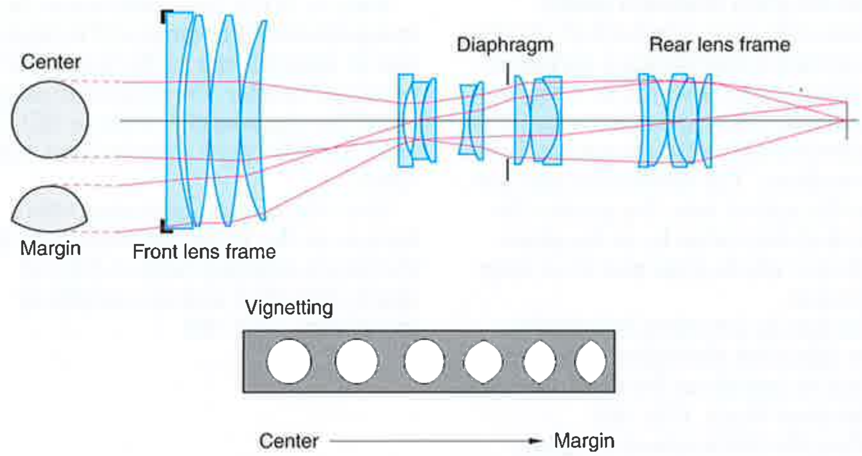


Fig.42 Vignetting and light distribution

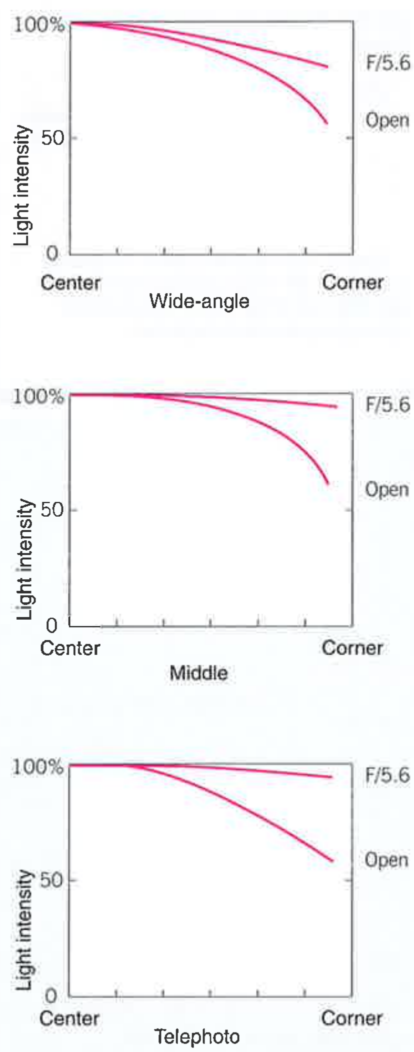


Fig.43 Light distribution at wide-angle, middle, and telephoto positions

The flat region in the center is smaller on the telephoto side, so rapid zooming can make the bright central circle appear to shrink, causing a light-ring effect.

2.11 Resolving Power and MTF

The imaging performance of a lens is often expressed as its resolving power. Resolving power is determined by photographing a chart with lines of various widths and seeing how far down the lens can still separate and reproduce the lines.

It is common knowledge, however, that a lens with high resolving power does not necessarily give good image quality. Resolving power expresses only the limit value of the lens. It says nothing about the lens' performance at comparatively low spatial frequencies, below the limit value.

This fact is particularly important in connection with television zoom lenses. A television camera converts an image to electrical signals. The bandwidth of the signal transmission path limits the fineness of detail (spatial frequency*) that can be reproduced.

* Spatial frequency is a measure of the fineness of a grid. It counts the number of lines (number of black-white pairs) contained in 1mm. The video frequency fv and the number of TV lines are related by the formula:

Spatial frequency (lines/mm)

$$= 65.873 \times \frac{\text{video frequency (MHz)}}{\text{diagonal image size (mm)}}$$

$$= 0.83 \times \frac{\text{TV lines}}{\text{diagonal image size}}$$

In the NTSC system, the transmission bandwidth is limited to 4MHz, which corresponds to the following frequencies on the image plane:

It is clear from the table below that whether a television lens has a resolving power of 75 lines/mm or 100 lines/mm does not make an important difference. What is more important is the reproducibility (contrast) of the image at lower spatial frequencies, such as 24 lines/mm for a 2/3″ SDTV camera lens.

Image size	Spatial frequency corresponding to 4MHz
2/3″	24.0 lines/mm
1/2″	33.0 lines/mm

Because of this shortcoming of resolving power, the total performance of a lens is evaluated by its modulation transfer function (MTF, also called optical transfer function, or OTF).

Before discussing the MTF of a lens, we shall consider how the faithfulness of an amplifier is measured electrically.

Suppose a waveform of gradually increasing frequency (sweep waveform) is input to an amplifier as in Fig. 44 and the output is measured. Up to point ⓐ the amplitude of the output remains constant, but at frequencies above ⓐ the amplitude decreases, until at point ⓑ the signal is not reproduced at all. The frequency characteristic of the amplifer can be indicated by drawing a graph with frequency on the horizontal axis and output amplitude on the vertical axis.

MTF is the same concept applied to a lens.

If a lens is used to focus an image of a chart on which the lines are gradually more closely spaced, as the spacing becomes closer the contrast of the image falls off, until the lines can no longer be resolved.

When the lines are widely separated, contrast is reproduced with nearly 100% faithfulness: white is white and black is black. When the lines become so fine and so closely spaced that black and white can no longer be distinguished and the image is a uniform gray, the contrast is zero.

Since MTF expresses the reproducibility of contrast, the MTF characteristic is shown by a graph with spatial frequency on the horizontal axis and contrast reproducibility on the vertical axis, as in Fig. 45.

Of the two lenses A and B with the MTFs shown in Fig. 45, which would make the better television lens?

If we compare resolving power, lens B wins. The high skirt of its MTF curve means that it can resolve high spatial frequencies. The transmission bandwidth of a television camera is limited, however, as noted above. For a 2/3″ camera, it is the contrast at 24 lines/mm, corresponding to 4MHz, that is important. Lens A, which has the higher MTF at lower spatial frequencies, would therefore be the better television camera lens.

Canon television zoom lenses are subjected to MTF evaluations in stages of manufacture as early as design development to yield optimal aberration balances for a variety of broadcasting formats.

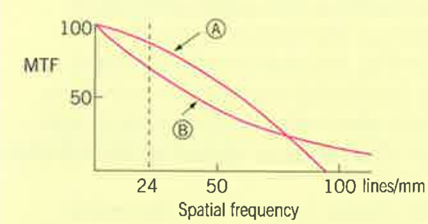


Fig.45 Comparison of lens performance by MTF

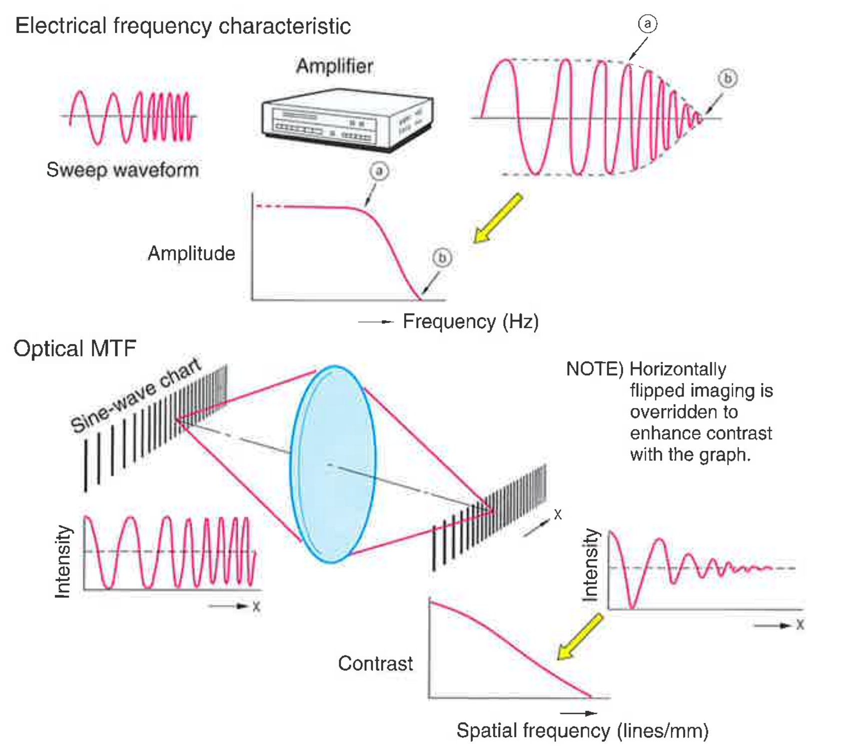


Fig.44 Electrical frequency characteristic and optical MTF

2.12 Chromatic Aberration

Chromatic aberration arises from dispersion—the property that the refractive index of glass differs with wavelength.

There are two types of chromatic aberration: longitudinal aberration (which corresponds to tracking error) and lateral aberration (which corresponds to registration error).

(1) Longitudinal chromatic aberration

This form of aberration causes different wavelengths to focus on different image planes. It corresponds to tracking error.

In a zoom lens, the amount of the longitudinal chromatic aberration varies as the lens is zoomed.

In Fig. 46 focal length is plotted on the horizontal axis and on-axis chromatic aberration on the vertical axis. The aberration is largest at the telephoto end.

If a large longitudinal chromatic aberration is left, tracking error will occur on the blue and red channels and cause color blurring, even when the tracking adjustment is optimal.

In a long-focal-length, high zoom ratio lens, chromatic aberration is the greatest problem, particularly the secondary spectrum, which is a high-order chromatic aberration.

The chromatic aberration of a lens is usually corrected at two wavelengths. The secondary spectrum is the residual chromatic aberration left at the wavelength midway between these two.

Two-wavelength correction is inadequate in a television camera that has three (red, blue, and green) channels. The secondary spectrum also has to be corrected.

The main cause of the problem is the residual chromatic aberration of the focusing group of lenses. It is difficult to solve because of inherent limits in the dispersion (wavelength characteristic of refractive index) of optical glass.

The secondary spectrum of Canon lenses is corrected by using flourite crystal, which has a different dispersion from ordinary optical glass, or by using a type of glass with an extraordinary dispersion characteristic.

(2) Correction of Longitudinal Chromatic Aberrations

The variation in the magnitudes of longitudinal chromatic aberration of a zoom lens is generally small between the wide-angle end and the middle, and is large on the telephoto side. In the lenses for HDTV, the longitudinal chromatic aberration at the focal length between the wide-angle end and the middle are designed to match with the standard of the CCD fixation positions mentioned above, so that the best

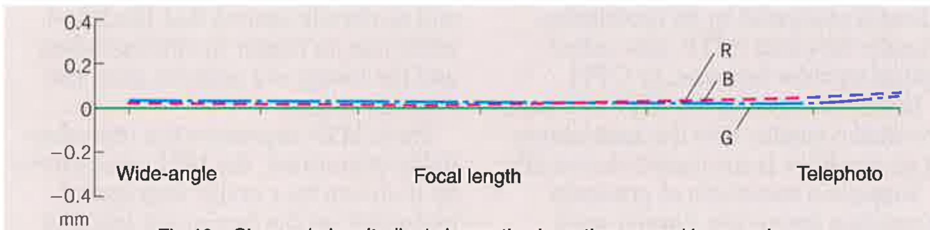


Fig.46 Change in longitudinal chromatic aberration caused by zooming

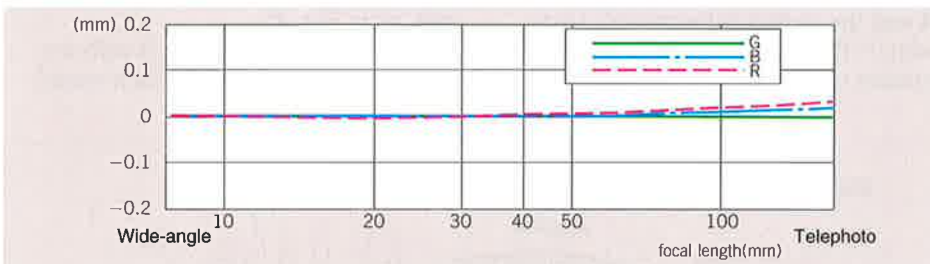
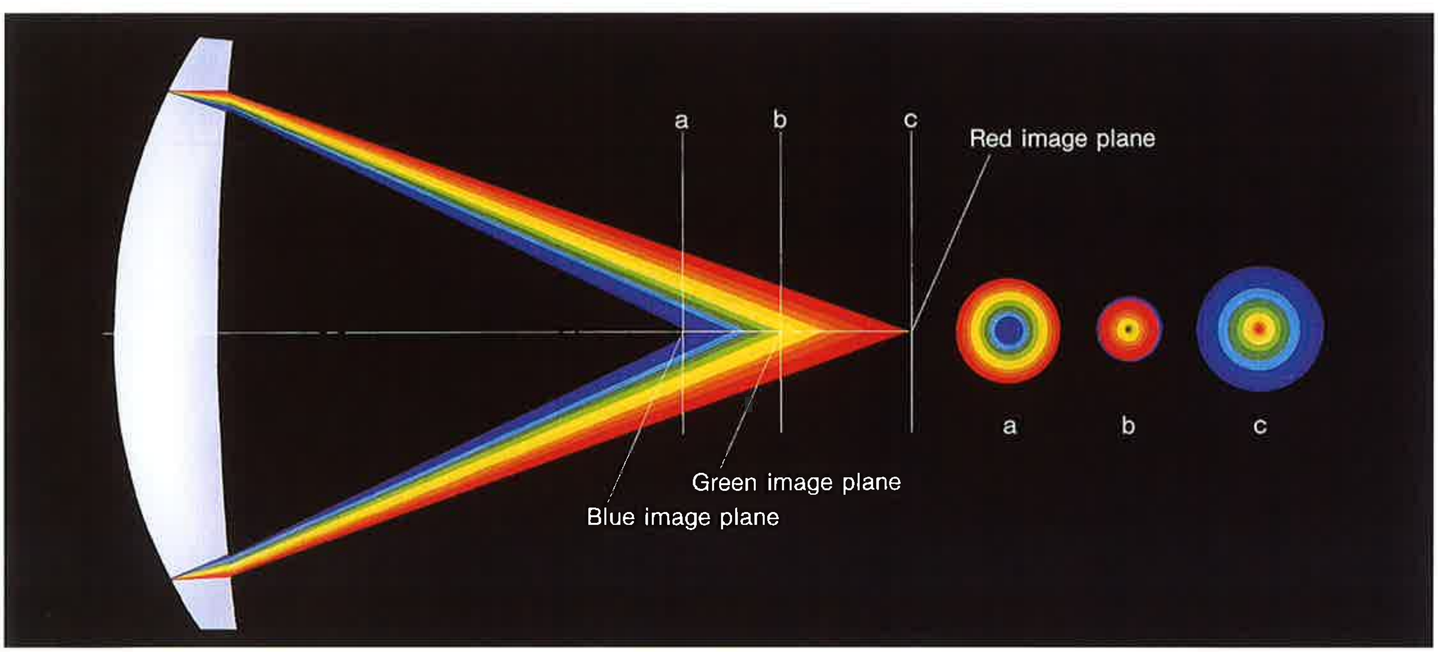


Fig.47 An example of the longitudinal chromatic aberration in a HDTV lens



efficiency on the CCD surfaces can be obtained for the entire focal length. (Fig. 47)

Though the secondary spectrum of longitudinal chromatic aberration tends to be large on the telephoto side of a zoom lens, its magnitude can be lowered by the proper use of fluorite and extraordinary dispersion glass.

Fig. 48 shows the capability of fluorite and the extraordinary dispersion glass in correcting chromatic aberrations, compared with ordinary optical glass.

In Fig. 48, the focal length is set at 100mm, and the magnitudes of the chromatic aberrations are magnified by 100 times. The chromatic aberration is corrected for two wavelengths, g-line (436nm) representing blue light and C-line (656nm) representing red light, and the remaining discrepancies from e-line (546nm) representing green light are shown. The amount of the discrepancies corresponds to secondary spectrum.

In comparison with the case in which ordinary glass is used, the amount of the secondary spectrum diminishes by about half when the extraordinary dispersion glass (S-FPL51*) is used, and is further diminished by half when fluorite (CaF_2) is used.

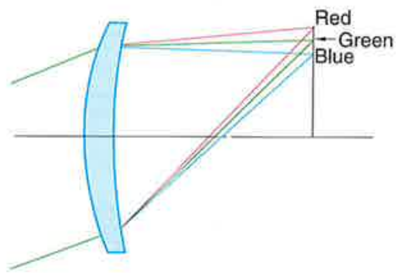
With the appropriate use of optical crystals and extraordinary dispersion glass, as shown above, it becomes possible to minimize chromatic aberrations which cannot be avoided in the use of ordinary optical glass.

(3) Lateral chromatic aberration

Lateral chromatic aberration occurs because the magnification of the image differs with the wavelength. In a television camera it causes registration error.

Lateral chromatic aberration also has a secondary chromatic aberration, making it difficult to correct all three of the red, blue, and green wavelengths at the same time.

In Fig. 49 focal length is plotted on the horizontal axis and lateral chromatic aberration on the vertical axis. Note how the red and blue registration lines trend across the green line as they move from wide-angle to telephoto.



(4) Correction of Lateral Chromatic Aberrations

According to aberration theory, chromatic aberration must be corrected for principal points as well as the focal length in order to correct lateral chromatic aberrations (Fig. 50). For a zoom

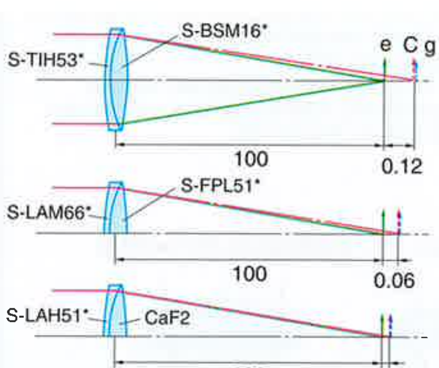


Fig.48 Comparison of second spectrum in cemented lenses

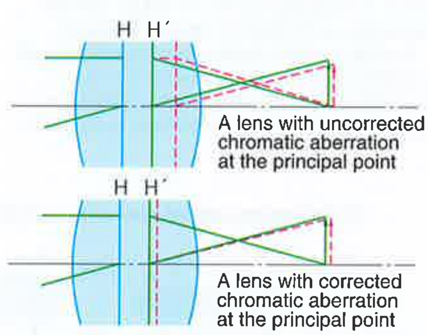


Fig.50 Lateral chromatic aberration

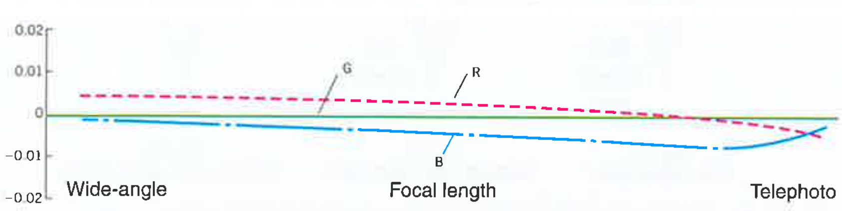


Fig.49 Change in lateral chromatic aberration caused by zooming

Practical Application of Fluorite and Hi-UD Glass

The fluorite having an unusual dispersion characteristic not found in optical glass, which can be used to remove chromatic aberration, was discovered by Abbe (1840-1905). At that time, natural fluorspar crystals were used, so applications were limited to small-diameter lenses such as the objective lenses of microscopes.

Canon noted the possibilities of fluorite long ago, studied the artificial crystallization technique, and succeeded in producing materials, 200mm or more in diameter, that can be used to produce large-diameter lenses.

Fluorite lenses are used in the focusing group of zoom lenses, and are especially effective for correcting chromatic aberration on the telephoto side.

On the other hand, the latest zoom lenses for TV broadcasting use a completely new optical material called Hi-UD (High Index Ultra Dispersion) glass. The Hi-UD glass features a high reflective index which allows correction of spherical aberration in addition to the above mentioned secondary spectrum correction effect.

Hi-UD glass lenses are used in the front lens group and compensator of a zoom lens to effectively correct not only chromatic aberration that occurs on the telephoto side but also other aberrations that occur due to focusing and zooming.

* S-FPL51, S-TIH53, S-BSM16, S-LAM66, S-FPL51 and S-LAH51 are registered trademarks of OHARA INC.

lens, it is required that the good correction conditions of the chromatic aberration of the principal points and focal length are maintained as a whole even with movement of the inside elements in the zoom lens.

Special attention has to be paid to the variators used within zoom lenses. They are powerful and move over a considerable distance, and in addition, their chromatic aberrations tend to be non-symmetric due to a necessity of compact size, which causes insufficient chromatic aberration correction at the principal points.

Fig. 51 shows the examples of the shapes of an ordinary conventional variator and a variator for an HDTV lens which has more symmetric chromatic aberration.

The use of fluorite or extraordinary dispersion glass is also effective in reducing lateral chromatic aberrations.

The lateral chromatic aberrations of an HDTV camera lens designed by this technique are shown in fig. 52. They have positive values for both B-ch and R-ch at the wide-angle end and negative values at the telephoto end, and their variations over the entire zooming range are minimized.

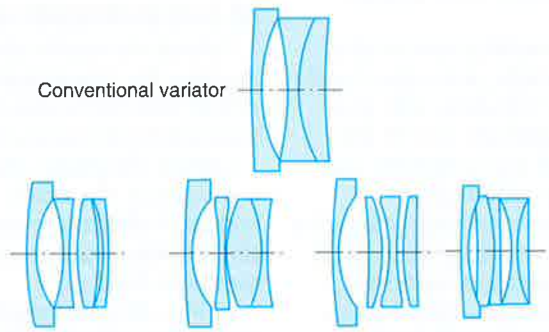


Fig.51 Variators with nearly symmetrically corrected chromatic aberration

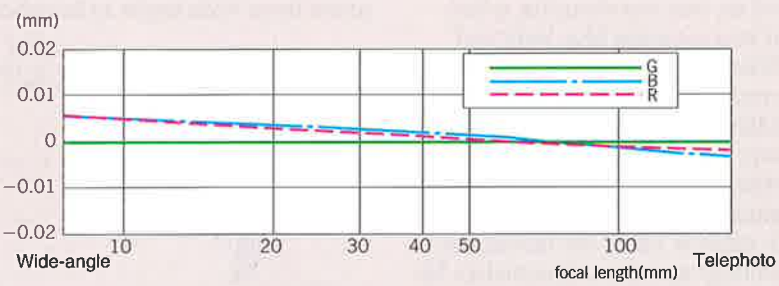


Fig.52 An example of the lateral chromatic aberration in an HDTV lens

Principles of Diffractive Optical Element

Shooting lenses are typically manufactured by machining optical glasses into a lens form for imaging through refraction.

Light has the quality of slightly varying in refractive index from wavelength to wavelength (which quality is called "dispersion" in optics terms). Lenses used over a broad range of visible wavelengths, such as broadcasting lenses and single-lens reflex camera lenses, may make differences in the imaging point associated with the slight differences in refractive index. Such differences are known as "on-axis color aberrations."

The slight differences in refractive index will in turn make differences in image size on the screen among different wavelengths (colors). These resultant differences are called "magnification color differences."

If a group of lenses that acts to condense light, as from the front broadcasting zoom lens, is considered, on-axis color aberrations can be corrected by using low-dispersion materials for convex lenses and high-dispersion materials for concave lenses so that the color aberrations produced by the convex lenses will be canceled by the concave lenses.

HDTV zoom lenses and super-telephoto lenses for single-lens reflex cameras make extensive use of fluorite, a lower dispersion crystal material, and a special, costly nitric material, such as UD glass, to reduce color aberrations to a minimum.

Diffractive optical elements represent a field of technology that manipulates the phenomena of "diffraction" of light to correct color differences. Commonly known as "DOE" (initial characters of Diffractive Optical Element).

If white (visible) light is condensed through a convex lens, images are formed in the ascending order of wavelengths, from blue, through green, to red, regardless of the material used, glass or fluorite (Figure (1)).

In contrast, if light is condensed through diffraction, images are formed in the descending order of wavelengths, from red, through green, to blue in a manner totally opposite to refraction (Figure (2)).

Use of an imaging action that works in opposition to refraction helps to correct color aberrations (Figure (3)).

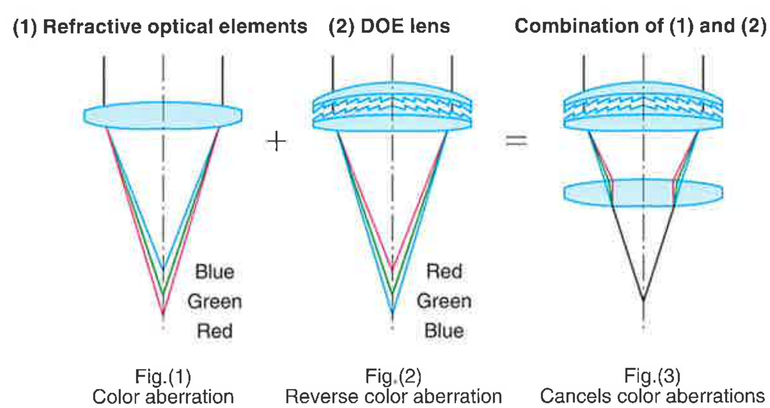


Fig.53 Principle of color aberration correction by DOE lenses

2.13 Seidel's Five Aberrations

The five basic aberrations of a lens are named after the researcher Seidel who classified them. In addition to them, there are the two chromatic aberrations described above.

Seidel's five aberrations are (1) spherical aberration, (2) coma, (3) astigmatism, (4) curvature of field, and (5) distortion.

The first four of these aberrations affect the sharpness of the image and degrade the MTF.

(1) Spherical aberration

Of the pencil of rays leaving a physical point on the axis of a lens, those that enter the lens at a large height above the axis are refracted to a different point on the optical axis from the paraxial focal point. If a screen is placed perpendicular to the axis at the paraxial focus, (at the paraxial image plane), instead of a point image, a small disc will be seen. This phenomenon is called spherical aberration. Spherical aberration is expressed as longitudinal aberration (distance on the optical axis). In Fig. 54 it is plotted with height at the entrance pupil on the vertical axis. On the horizontal axis is plotted distance from the paraxial focal plane at which the ray crosses the optical axis.

Spherical aberration can be greatly improved by stopping down the lens. Two or three stops down from full aperture it almost completely disappears. If the aperture is stopped down further, diffraction gradually appears, so the sharpness gained is lost again if the lens is stopped down too far.

(2) Coma

Even if a lens is completely corrected for spherical aberration, other types of aberration appear at off-axis points. Coma is one of these. Rays incident at an angle to the optical axis are not focused to a point on the image plane, but form a comet-like image with a tail.

The tail may point toward the center of the image plane or in the opposite direction, giving rise to inward coma or outward coma. An object which contains concentric lines with respect to the optical axis will suffer serious blur along one edge of each concentric line. If a lens is not corrected for coma, contrast around the edges of the image will be poor.

Coma can be improved by stopping down the lens. (Fig. 55)

(3) Astigmatism

A lens corrected for spherical aberration and coma will still not focus a point off the optical axis to a point image. Instead, the image will be oval-shaped, or will consist of one of a pair of lines called focal lines. This aberration that prevents a point object from focusing to a point image is called astigmatism. If the focusing plane is moved backward and forward, a single point will be found where a sharp image is formed in the center of the plane, but away from the center, the point of sharp focus is not unique. Concentric circles come into sharp focus at one point; radial lines at another. A point gives rise to two perpendicular line images: the sagittal image line and the meridional image line. In the foreground and background of the focused object, image blur occurs in a concentric pattern, giving the lens what is termed "uneven blur." (Fig. 56)

Stopping down the lens aperture and thereby increasing the depth of focus absorbs astigmatism to some extent, but does not remove it completely. Resolving power charts with concentric circles and radial lines are used for testing astigmatism. (Fig. 57)

(4) Curvature of field

Curvature of field is the failure of a lens to focus a plane object as a plane image. If the center of the object is brought into sharp focus, the edges will be out of focus. If the edges are brought into sharp focus, the center will be out of focus. The image planes formed by the sagittal and meridional lines resulting from astigmatism are not flat planes, but are curved. If the two planes are separate, the image plane of practical interest lies between them, and this plane is usually also curved. This curvature is called curvature of field. Like astigmatism, curvature of field can be

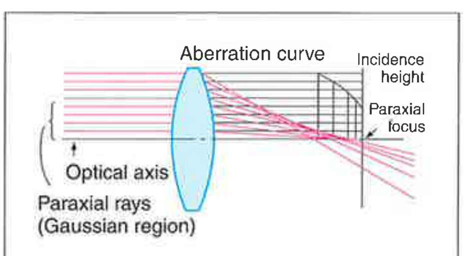


Fig.54 Spherical aberration

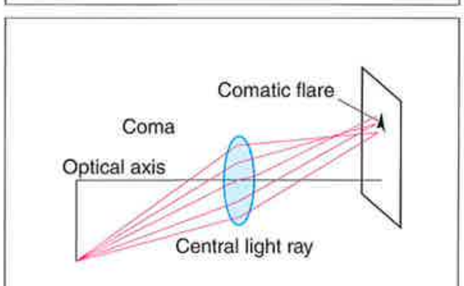


Fig.55 Coma

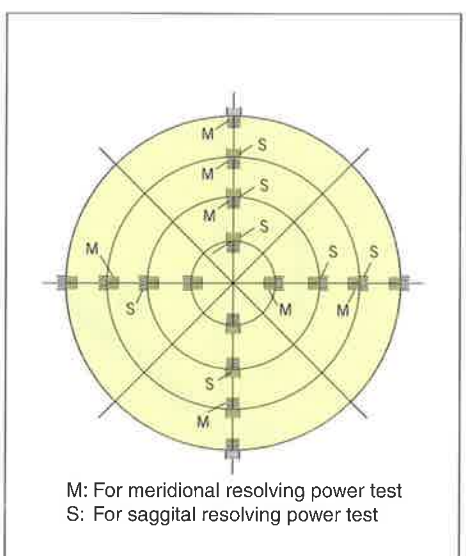


Fig.57 Resolving power test chart

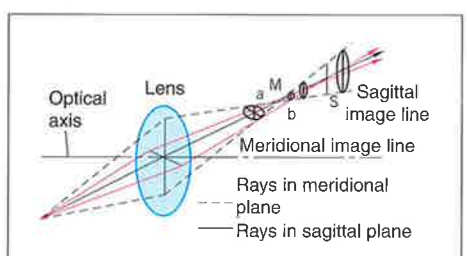


Fig.56 Astigmatism

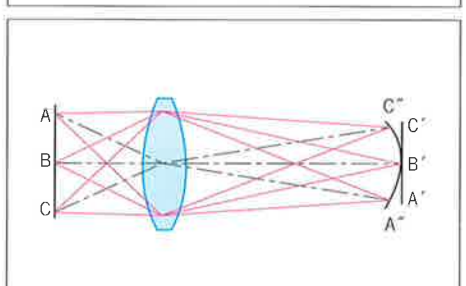


Fig.58 Curvature of field

absorbed by stopping down the lens to increase the depth of focus. (Fig. 58)

2.14 Large-Aperture Aspherical Lens Technology

Traditionally, lens elements having a spherical surface have been commonly used as within lenses intended for television imaging; mainly because the lens surface is polished to relatively high precision and spherical lenses are easy to volume-produce.

Spherical lenses are characterized by light more strongly refracted in the margins rather than the center. For this reason, a single spherical lens (convex lens) is unable to condense rays of light at one ideal point, resulting in a flared image (spherical aberrations). To remove flares, more convex shaping needs to be added to ease the share of aberration per lens or concave lenses need to be introduced to produce counter-aberrations. To use spherical lenses alone and still attain enhanced performance, many lens elements would have to be employed, resulting in an oversized lens assembly.

An aspherical lens, as its name implies, does not have a spherical lens surface but has an optionally shaped surface. As shown in figure 60, for example, an optimally shaped aspherical lens that condenses rays of light at one ideal point each produces an extremely sharp, spot image with little flare.

Thus, a single side of an aspherical lens successfully corrects flares, offering an optimal solution to combining enhanced optic performance with compact, lightweight lens assembly geometry.

The concept of aspherical lens tech-

Paraxial Theory and Aberration Theory

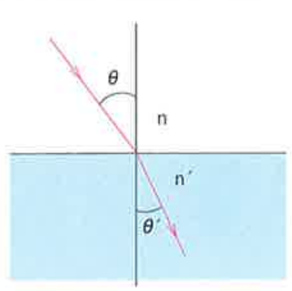
In Snell's law of refraction

$$\frac{n}{n'} = \frac{\sin\theta'}{\sin\theta}$$

when θ is extremely small, the approximation $\sin\theta \simeq \theta$ can be used. In paraxial theory it is assumed that $\sin\theta = \theta$. Under this assumption there is no aberration and an ideal image is formed.

Aberrations in optical systems occur because this approximation is not true. If $\sin\theta$ is expanded into a power series and approximated by the terms up to the 3rd power, the resulting theory is called 3rd-order aberration theory. That is the theory Seidel used in classifying the five aberrations.

If the approximation is extended to the 5th-power term, the theory is called 5th-order aberration theory, and twelve more forms of aberration arise. This 5th-order aberration theory is what propelled the Japanese optical industry to the world-class level. Its practical application was worked out by Dr. Yoshiya Matui of Canon.



Large-aperture Aspherical Lens Technology

Figure 59 shows correlations between the zoom ratio of field zoom lenses developed by Canon to date and the lens overall length.

Broadcasting zoom lens users had feared that proportional increases in the zoom ratio and the lens overall length as marked by a chain line in Figure 59 might lead to a bulky, heavy and hard-to-carry product by the time the zoom attained a 100-fold increase.

In 1999, when HDTV began to claim popularity, a market survey was conducted to pave the way for the development of a field high-magnification zoom lens. The survey identified three broad areas of customer satisfaction.

(1) Superior optic performance compatible with an HDTV system

(2) Compact, lightweight geometry to ease setup and handling

(3) Vibration insulation

The survey spurred Canon to introduce large-aperture aspherical lens, and associated new optics design and large-aperture lens machining technologies to combine enhanced optic performance with compact, lightweight geometry in the entire lens family in its development of the XJ86x9.3B (announced and released in 2000).

Field high-magnification lenses that have been unveiled in the wake of the XJ86x9.3B have a constant lens overall length, regardless of the zoom ratio.

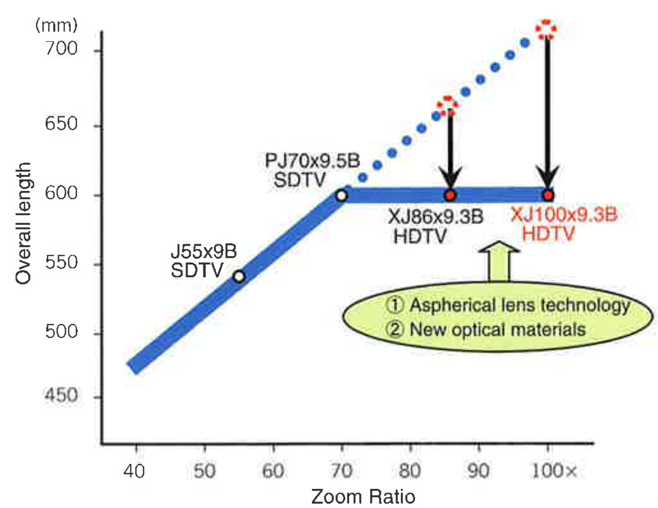


Fig.59 Zoom ratio and overall length of broadcasting field lenses

nology has been known for a long time, but it requires significant advances in lens machining capabilities to address the critical requirements for precision posed by broadcasting zoom lenses.

Techniques available for machining aspherical lens available include:

(1) Aspheric lens polishing, which polishes the surfaces of medium-sized to large aspherical lenses little by little using a small-aperture polishing tool until an ideal aspherical geometry is worked out.

(2) Glass molding, which molds small-aperture materials into an ideal aspherical geometry.

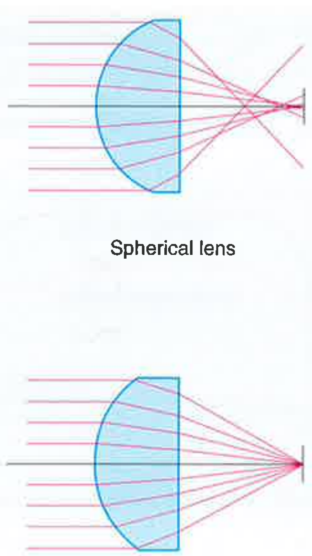


Fig.60 The effect of aberration correction for aspherical lenses

2.15 Distortion

Whereas the aberrations described above are all related to the sharpness of focus of the image, distortion concerns the overall shape of the image. Distortion is usually expressed as a percent—the percent of the ideal image height by which the points depart from their position in the ideal image. Let Y be the image height of a principal ray on the image plane, and let $\overline{Y}$ be the ideal image height. The distortion is then:

$$\text{Distortion (\%)} = \frac{Y - \overline{Y}}{\overline{Y}} \times 100$$

Distortion alters the exact resemblance of the image to the object, giving either a pincushion effect or a barrel effect. (Fig. 61)

Distortion caused by a television lens is expressed in the same way as the

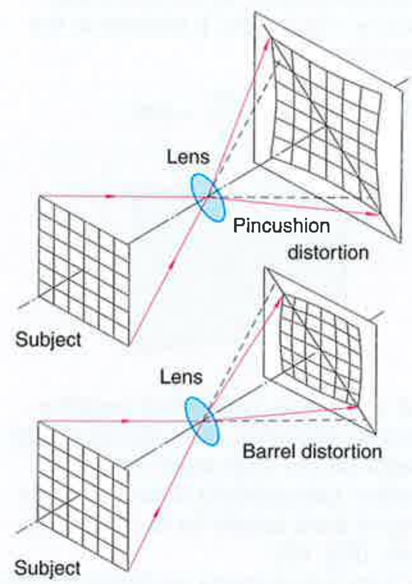


Fig.61 Distortion

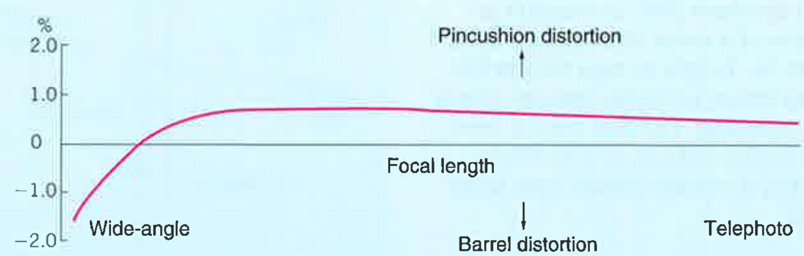
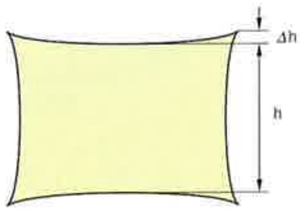


Fig.62 Television lens distortion

distortion caused by the television camera—as the $\Delta h/h$ percent in the figure below.

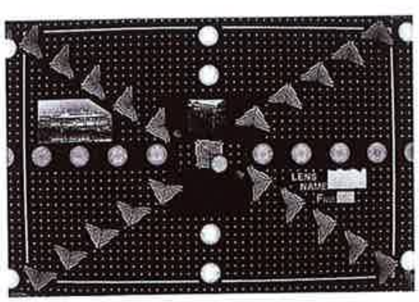
$$\text{TV. Dist } (\%) = \frac{\Delta h}{h} \times 100$$

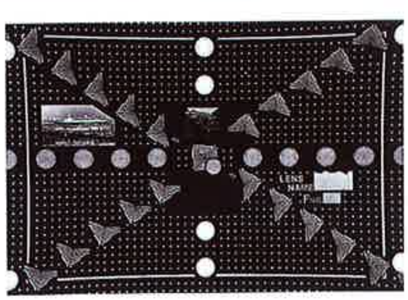


A zoom lens usually has negative (barrel) distortion at its shortest focal length (at the wide-angle end), and positive (pincushion) distortion at its longest focal length (at the telephoto end). (Fig. 62)

Distortion remains unchanged even if the lens is stopped down.

Lens-caused distortions threaten horizontally extended HDTVs with a ratio of 6:9, as they have distortions enhanced by about 30%. Correction of distortion of a zoom lens is complicated because the height of rays vary in the focusing group or in the variator group during zooming. For this reason, new optical configurations of a focusing group and a variator group have been devised.





2.16 Coatings

If the refractive index of glass in n_G, at the interface between glass and air, orthogonally incident light will be reflected with a reflectance of:

$$r = \left(\frac{n_G - 1}{n_G + 1}\right)^2$$

When $n_G = 1.5$, $r = 4\%$

It follows that 4% to 10% reflection occurs at each lens surface. In a zoom lens, which has many lens surfaces, this can amount to a considerable loss. Multiple reflections within the lens system can also cause flares and ghost images. To reduce troublesome reflections, lens surfaces are given special coatings.

A coating is a thin, transparent film on the lens surface that uses interfer-

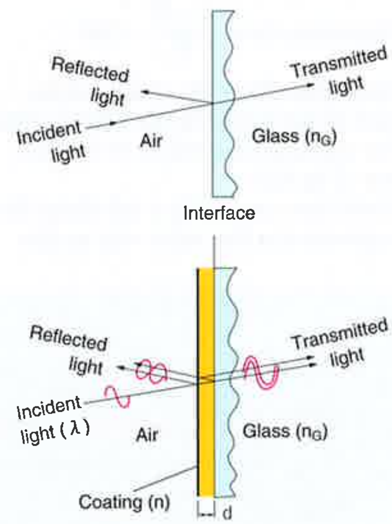


Fig.63 Effect of coating on reflection

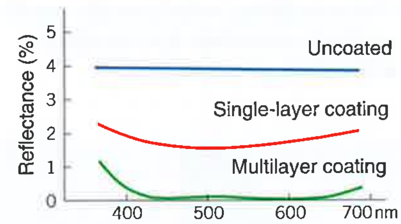


Fig.64 Single-layer and multilayer coatings

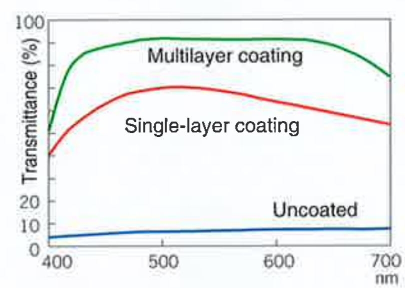
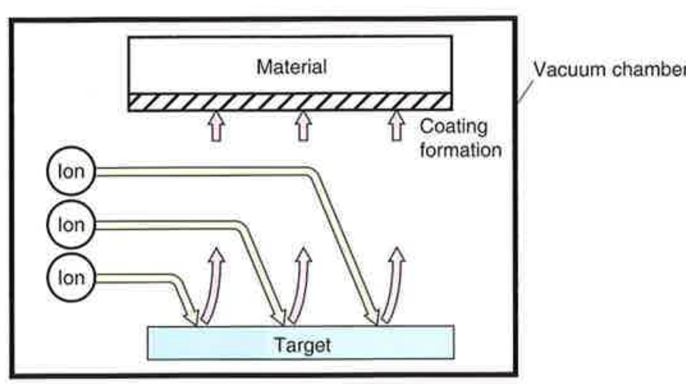


Fig.65 Effect of coating in a zoom lens

Sputtering

Collision of fast ions (main components are ionized inert gases) against a target (a coating material) causes atoms and molecules to sputter from the target surface owing to the momentum exchange. This symptom is called sputtering. The method by which sputtered materials are built up on the opposing material to form a coating as shown in figure, is called a sputtering method (or simply called sputter or sputtering). The sputtering method features high-density hard coatings built up without substrate heating, because of high adherence to substrate by heightened energy of sputtered materials.



ence effects to reduce reflection and increase transmittance.

If the refractive index of the lens glass is n_G, the refractive index of the coating material is n, and the thickness of the coating is d, then the conditions that prevent reflection by single-layer coatings are: (Fig. 63)

$$n = \sqrt{n_G} \text{ (Amplitude condition)}$$
$$n \cdot d = \lambda / 4 \text{ (Phase condition)}$$

Multilayer coatings that prevent reflection more effectively than single-layer coatings have been developed. Most broadcasting zoom lenses have multilayer coatings. (Figs. 64 and 65)

Vacuum Evaporation

Lenses are coated in a large vacuum chamber called a bell jar. (Fig. 66) The coating material, such as magnesium fluoride (MgF_2), is heated by an electron beam at the bottom of the jar. It evaporates, travels through the vacuum, and is deposited on the lens surface. Vacuum evaporation is characterized by easy coating process with many materials. It also shows a performance advantage in high-precision optical thin coating.

A multilayer coating is built up by evaporating different materials in alternate sequence.

A dichroic coating is created in the same way, but it has more layers than an anti-reflection coating, and the process is more complex.

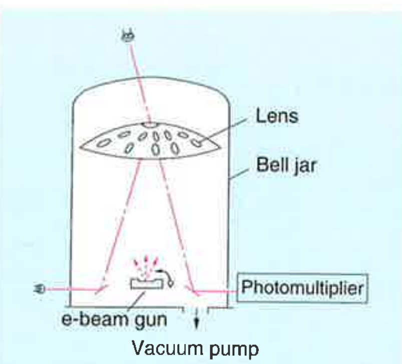


Fig.66 Vacuum evaporation process

2.17 Comparison of Lenses with Different Image Sizes

Modern TV cameras have image sizes of 2/3″, and 1/2″. It is frequently necessary to compare lenses with different specifications. Here is some simple advice on three methods of comparison by: (1) focal length, (2) F-number, and (3) depth of field.

(1) Focal length

If you want to use a 1/2″ camera to shoot the same scenes as a 2/3″ camera, what lens do you need?

From Section 2.3, the angle of view w is:

$$w = 2\tan^{-1}\frac{y'}{2f}$$

y': Image size
f: Focal length

To get the same angle of view with the smaller y', it is only necessary to choose a smaller f.

In other words, if the ratio of the image size to the focal length is the same, the angle of view is the same.

Taking Canon's lenses as an example, the J17e × 7.7 (2/3″), and KH16e × 5.7 (1/2″) all have nearly equal angles of view. (Fig. 67)

(2) F-number

To state the conclusion first, to maintain the same brightness, the smaller the image size of the lens is, the smaller (brighter) its F-number needs to be. In other words, the F-number should be proportional to the image size.

In a television camera the number of raster lines is the same regardless of the image size, so reducing the image size reduces the area of the pixel. The amount of light received by the pixel therefore decreases as the image size decreases. This decrease has to be compensated for by reducing the F-number in the same proportion. (Fig. 68)

A film camera is different; the same F-number can be used with any image size. The pixel on film is the grain of silver chloride, the diameter of which is the same for all film sizes. As the image size is reduced, however, resolving power is lost, even though the F-number is not affected.

(3) Depth of field

When the image size changes, the diameter δ of the permissible circle of confusion changes in proportion. (Section 1.3)

If the focal length f and F-number F are selected as described in (1) and (2) above, the depth of field will remain the same. This is shown by the equation in Section 1.3.

In other words, if the focal length and F-number are selected in proportion to the image size, the depth of field will stay the same.

The depth on the focal point side, however, decreases as the image size decreases (because of the decreasing δ and F_{NO}), so tracking has to be more carefully adjusted.

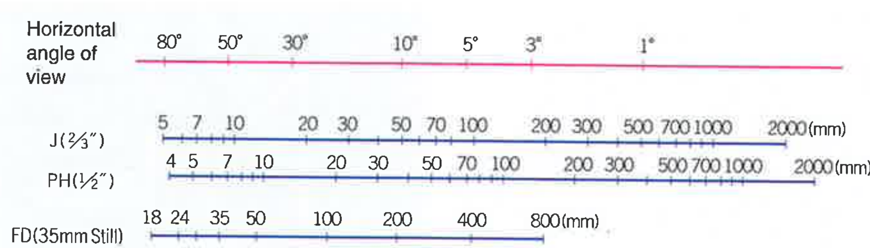


Fig.67 Comparison of lenses with different image sizes (1)

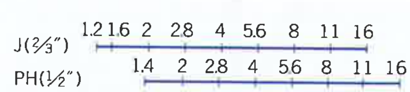


Fig.68 Comparison of lenses with different image sizes (2)

3 CCD camera Lenses

When the first edition of this book was published, pick-up tubes such as plumbicons and saticons were being used for color TV cameras.

Subsequently, however, CCDs, a kind of solid state imaging device were applied to TV cameras, and the use of CCDs has been increasing rapidly since that time. With the replacement of pick-up tubes by CCDs, the required lens performances became very strict in some respects.

3.1 Differences between Pick-up Tube Cameras and CCD Cameras

In the image pick-up tube camera, as shown in Fig.69, tubes were supported on the alignment housing which contains color separation prisms. And the focus could be adjusted when the tubes moved their positions back and forth. Furthermore, registration and linearity could be adjusted by electrically controlling the deflection of the electron beams. Though these adjustment techniques were used originally to correct errors that the tubes had in themselves, adjustments of the lens aberrations were carried out as well as a result.

For this reason, with regard to the lens for pick-up tube cameras, longitudinal chromatic aberration, lateral chromatic aberration and distortion can be adjusted by the camera. Therefore, the absolute magnitude of these aberrations dose not pose any practical problems, as far as their fluctuations are small. However, these adjustments are not possible on CCD cameras because CCD chips are fixed to the color separation prisms.

Since CCDs are free from the burning, high-intensity light may enter the lens. Therefore, ghosting and similar problems must be prevented more carefully when CCDs are used.

The required characteristics for a CCD camera lens are summarized in Table. The following are the explanations of each item.

Characteristics of CCD cameras and required lens efficiency

Fixation of CCD position	Standardization of CCD installation position. Diminution of longitudinal chromatic aberration. Optimization for CCD position.
Registration not adjustable	Decrease in the absolute value of lateral chromatic aberration.
Freedom from distortion	Distortion reduction.
Uniform responses all over the area	Improvement in the peripheral MTF.
No burning	Reduction of ghosts and flares.
Miniaturization of the camera	Miniaturized and lightweight lenses.

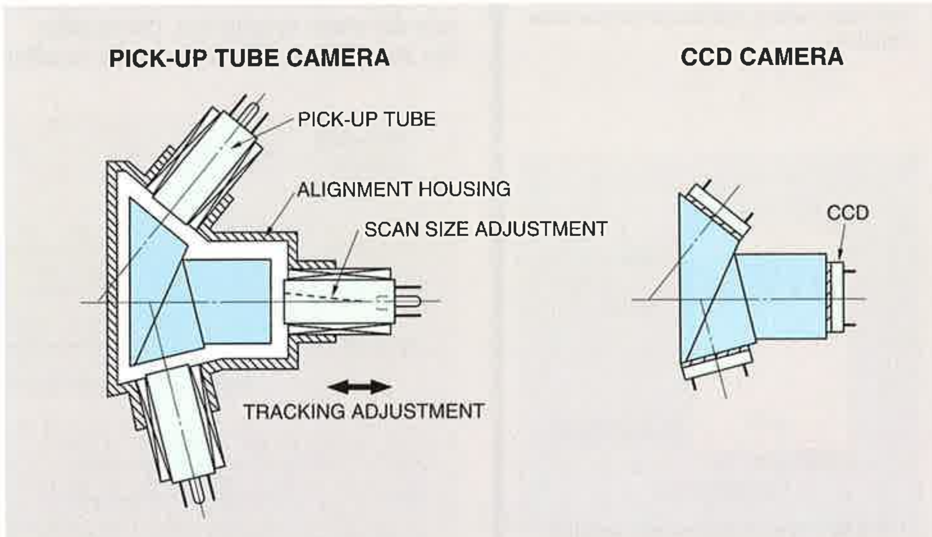


Fig.69 Differences between a pick-up tube camera and a CCD camera

3.2 Reduction of Ghosting and Flaring

Because CCD cameras are free from the nuisance of burn-in, regardless of the broadcasting format, they could allow highlights, such as sunlight and illumination, to enter the screen. Therefore, in a CCD camera, ghosting and flaring occurring when the light source is in the image area cause trouble, though they are not detected in a pick-up tube camera.

Some of them are caused by reflections between the CCD surfaces and the surfaces of the lens elements, scattering by the inner surface of the lens barrel or the lens edges, etc.

Concerning the reflection from the lens surface, multilayer anti-reflection coating newly developed for TV lenses is applied to increase the transmission and simultaneously diminish the flaring.

In order to prevent the scattering from the lens edges, a special anti-reflection paint is applied. This paint is made of high refractive index medium and minimal black particles as shown in Fig. 70, and works very well to diminish the reflection from the inner surfaces of the glass.

To prevent scattering reflection inside the lens barrel, such methods as painting of frosted black paint, anti-reflecting grooves, and hair flocking are employed appropriately. (Fig. 71)

3.3 Reducing the Size and Weight

As HDTV cameras are becoming smaller, lenses which are well balanced with the HDTV cameras and are easy to use are now in demand.

It is very difficult to improve the optical characteristics and performance of a lens for the HDTV camera, and simultaneously to achieve the reducing size and weight. Smaller size is accomplished by the use of light weight glass, the use of appropriate glass and the introduction of the new lens configurations.

Improvement of operation is achieved by the introduction of ergonomic design based on human technology, in addition to the light weight design using three-dimensional CAD (computer aided design).

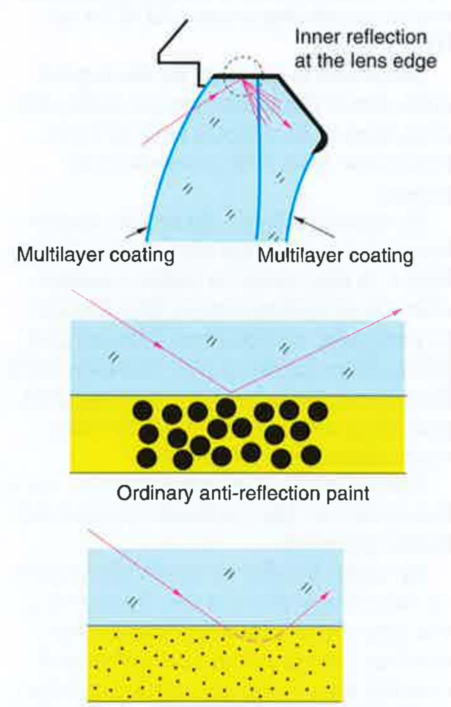


Fig.70 Anti-reflection paint for the inner surface of glass

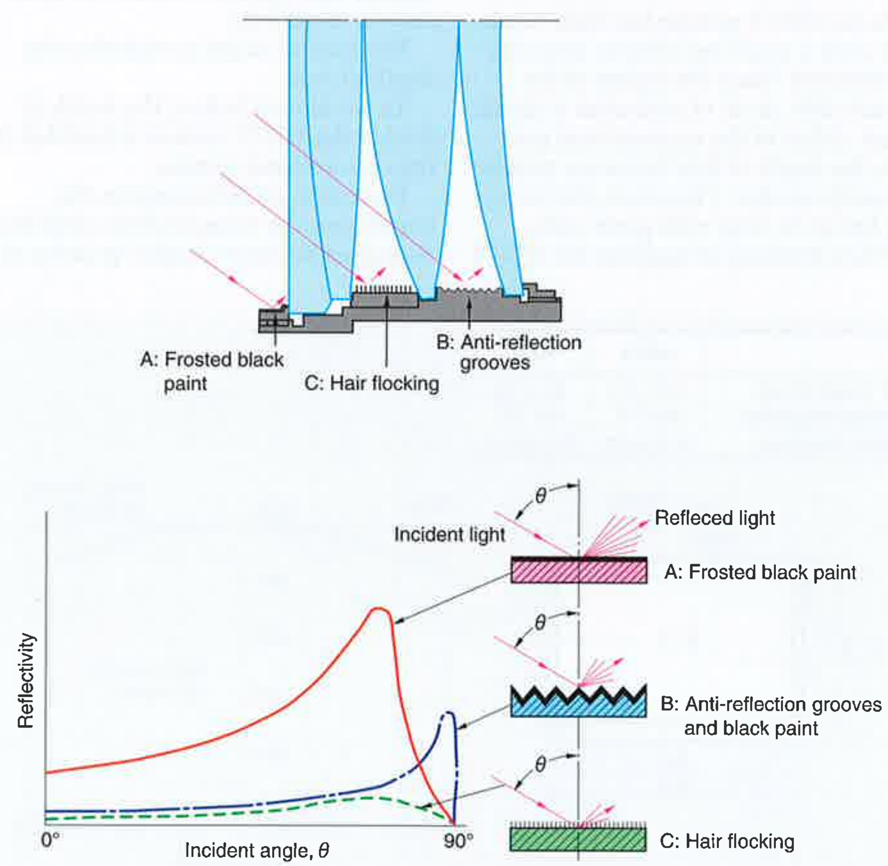


Fig.71 Anti-reflection measures for the inner surface of a barrel

4 HDTV System

4.1 Comparison with the NTSC System

Whereas one field of the conventional NTSC system consists of 525 scanning lines, the number of scanning lines is more than twice for the HDTV system (see the notes). Furthermore the density of the scanning line is even higher because the HDTV system has an aspect ratio of 16:9, which is wider than that of the NTSC system. The spatial frequency required for the HDTV system is about 2.5 times that required for the NTSC system (Fig. 72).

Overall, the resolution of the HDTV system is 2.5 times that of the NTSC system, and therefore the lens, which is the eye of the system requires much higher performance than the conventional lens uses.

4.2 The Depth of Field for HDTV System

As the HDTV system has high resolution even a small out-of-focus area can be detected. Since the radius of the permissible circle of confusion is about a half of that of the conventional system, the depth of field becomes proportionately smaller. Therefore, the focusing has to be done with great care.

When thinking of applying the HDTV system to motion pictures, the problem of the depth of field cannot be ignored. HDTV system is of benefit to the motion picture industry too, because they can produce high-quality images and the images can be easily processed electrically. When making pictures, a large aperture is often used to throw the background out of focus and to clearly distinguish the subject. For this reason, large-aperture lenses with small F-numbers are used.

A series of HDTV lenses with fixed focal lengths and an F-number of 1.2 have been developed for that purpose.

4.3 The Sensitivity of the HDTV System

Two factors have to be taken into consideration when comparing the sensitivity of the HDTV system with that of the conventional system.

The first consideration is the fact that the HD camera has an aspect ratio of 16:9. This makes the sensitive area smaller and causes a 10-percent difference in sensitivity.

The second factor is related to the depth of field.

As mentioned before, the depth of field in the HDTV system is half that in the conventional system.

Therefore, on HD cameras, the lenses must be stopped down until their F-number becomes double in order to get the same depth of field as that in the conventional system. This reduces the sensitivity to one forth.

Thus explained, HDTV systems have their practical sensitivity degraded due to the implications of the depth of field, but solid-state coupling components have come to offer improved sensitivity.

4.4 Aberration Correction for HDTV Lenses

The pixel size is less than a half in the HDTV system, and therefore the spread of a point image caused by a spherical aberration, coma, etc. should be diminished to less than a half.

Even if the image is slightly out of focus, MTF is greatly influenced. The Fig. 72 shows how MTF varies when the focus changes. The amount by which an image is out of focus which causes only a 10-percent MTF loss in an NTSC lens causes a 50-percent MTF loss in an HDTV lens, which is not acceptable. This suggests that reducing the curvature of field has an important role in improving corner MTF in an HDTV lens.

Distortion is affected by the aspect ratio. Since the image area is wide, the distortion of horizontal lines is more noticeable than with conventional lenses.

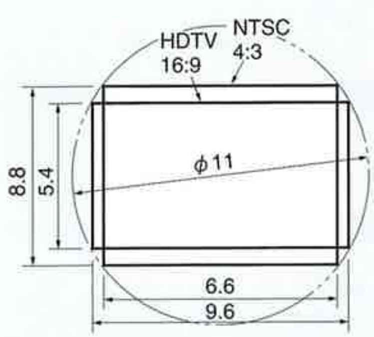
To correct lateral chromatic aberration and longitudinal chromatic aberration, it is necessary to make considerable use of optical crystal like fluorite or particular extraordinary dispersion glass. Some kinds of new extraordinary dispersion glass have been developed, providing new possibilities for chromatic aberration correction.

To realize the high performance mentioned above, the methods mentioned below are used.

By using fluorite or newly developed extraordinary glass in the front group, not only chromatic aberration correction but the spherical aberration and comatic aberration are minimized due to the alleviation of the power of each lens element.

Variators must use lens elements with small radii because they require a lot of power. In this case, aberrations are corrected by separating a cemented

	HDTV	NTSC
2/3″ image format	9.6 × 5.4	8.8 × 6.6
Nominal frequency	800 TVL	400 TVL
Spatial frequency	74 lines/mm	30 lines/mm



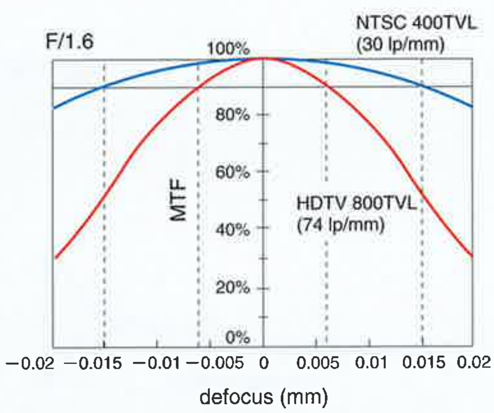


Fig.72 Comparison between HDTV and NTSC systems (for 2/3″ format)

element or increasing the number of lens elements.

4.5 Standardization of Lens-Camera Interfaces

To make the HDTV system easy to operate for users in various fields, the system is required to exhibit full performance irrespective of the combination of the lens and the camera. For this reason, broadcasting stations, camera manufactures and lens manufactures discussed standardizing the interface, and made a proposal. Some of the proposed standards are shown in the table.

These interface standards were considered mainly in the EBU (European Broadcasting Union) and enacted (see the note).

Note: Specifications for the optical, mechanical, and electrical interface between lens and camera for 1″ HDTV CCD cameras. EBU. 1991.

4.6 Compatibility between 2/3″ SDTV and 2/3″ HDTV

The optical interfaces for lens and camera of the 2/3″ SDTV system (Canon designation: B4 mount) are made compatible with those of the 2/3″ HDTV system to meet the user demand that they want to use conventional B4-mount lenses with the HDTV system.

As shown in Figs. 73 and 74, the both systems use the same mechanical interface. For the optical interface, the overall thickness of glass blocks is the same but the glass material and thicknesses of individual glass blocks are different. The reason is that the offset +30 µm of the B-G used by the SDTV system is not sufficient to obtain high MTF at the high spatial frequencies handled by the HDTV system and consequently the glass block diversion is modified so that the B-G becomes minimum even when a 2/3″ SDTV lens is attached to the HDTV camera, thus maintaining the compatibility.

Fixed-focus lenses with relatively small chromatic aberration can be used with the HDTV system. In zoom lenses for SDTV, however, chromatic aberration remains within the tolerance specified for the SDTV system and so it is recommended that the lenses optimized for HDTV be used with the HDTV system.

Correction of aberrations of HDTV lenses is summarized in the next chapter.

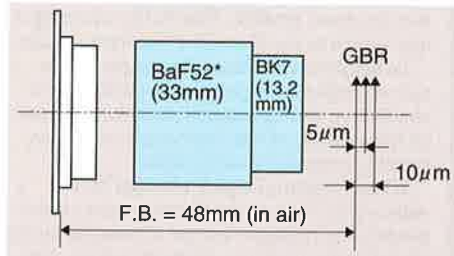


Fig.73 HDTV CCD fixation position

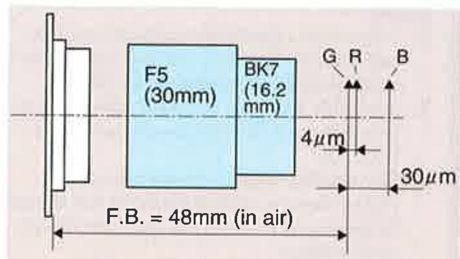


Fig.74 SDTV CCD fixation position

2/3″ HDTV Camera Optical Interface Specifications and Optical Requirements

On-axis color aberration reference values	R-G: +10µm, B-G: +5µm Using a glass block of 33.0mm (BaF52*) + 13.2mm (BK7)
Flange-back	48.0mm (in air)
Imaging circle	φ 11.0mm min.

* BaF52 is a registered trademark of SCHOTT AG.

Diffraction Limit

A lens that has no aberration and that can image a point object ideally is called an aberration-free lens. However, some blurring appears even when the aberration-free lens is used. This is caused by the phenomenon called diffraction.

Diffraction occurs because light has the characteristic of waves. Although light generally travels in straight lines, it has the characteristic of turning in behind an object just like waves on the water. This characteristic of light causes the blurring in the aberration-free lens.

The area of the blurring caused by diffraction is small when a lens with small F-number is used, and it becomes larger as the lens is stopped down. Therefore, the more the aberration-free lens is stopped down, the lower its MTF becomes. Fig. 75 is the MTF of an aberration-free lens shown as parameters of the spatial frequency and F-number.

As shown above, there is a point in an optical system where the performance does not improve, no matter how much the aberration is reduced. This is called the diffraction limit.

There is a residual aberration in a general zoom lens or a camera lens. So the blurring caused by the aberration is larger than that caused by diffraction when the F-number is small. The lens is nearly being free of aberration when it is stopped down until the F-number is about 5.6. If the lens is stopped down further, however, the MTF is not increased, but is lowered.

In an HDTV lens, the influence of diffraction cannot be ignored because the evaluation frequency is high. When using a HDTV camera, care must be taken not to stop down the lens too much, and for this reason, ND filter or the like is attached to the lens or camera.

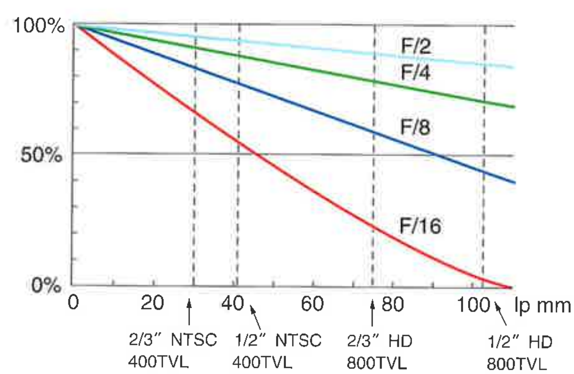


Fig.75 Theoretical MTF for an aberration-free lens

Advantages of Lenses for HDTV

The lenses for HDTV have the following advantages over the lenses for SDTV:

1) The image is formed uniformly from the center to the periphery of the frame. (Fig. 76)
2) The image uniformity is maintained over the focusing range from the wide-angle end to the telephoto end. (Fig. 77)
3) The image is formed uniformly from object distances from infinity to short distance. (Fig. 77)
4) Especially at the telephoto end, lower longitudinal and lateral chromatic aberrations.

The above advantages are prominent at the nearly maximum aperture.

Lens aberrations may improve as the aperture becomes smaller. That is, the advantages may lessen as the F-number becomes greater.

To keep up with these advantages, extensive expertise in respective of optics design, simulation, optical material and other relevant technologies is of vital importance to the successful correction of aberrations.

When compared with traditional SDTV lenses, HDTV products dictate quality control powered by certain concepts of manufacturing expertise (such as 1 to 4 below) to reproduce their design superiority in the form of product quality.

1. Tolerances (allowable variations from design values) of optical and mechanical parts must be tightly managed. (Fig. 78)
2. Assembly accuracy of optical and mechanical parts must be very closely controlled. (Fig. 78)
3. The number alignment and adjustment steps related to optical performance should be increased to attain the specified design performance.
4. MTF must be maximized at the high spatial frequencies required for HDTV.

For this reason, use of an HDTV lens family optimized to work with HDTV is recommended for HDTV systems.

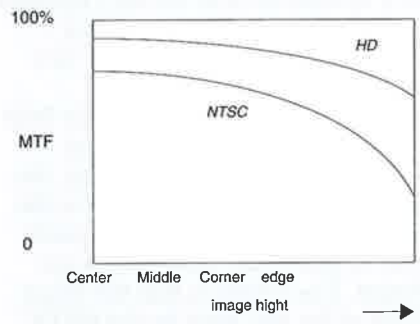


Fig.76 MTF angle of view characteristics

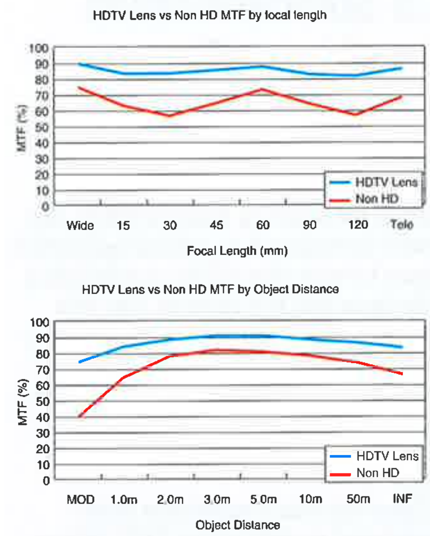


Fig.77 MTF zoom and distance characteristics

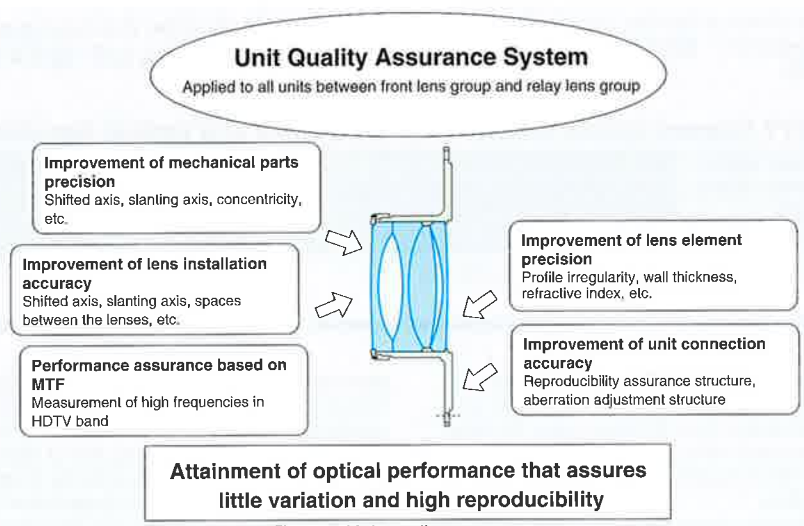


Fig.78 Unit quality assurance

4.7 Digital Cinema Lenses

Optical features of lenses for Digital Cinema are as follows:

1) The contrast and resolution are high from the center to the periphery of the frame, ensuring an optimized MTF profile over the image plane.
2) The image quality is high in the entire focusing range, from the center to the periphery of the frame, with minimum chromatic aberrations.
3) The image quality is natural with small distortion (the distortion of the fixed-focus lenses is extremely small).
4) During zooming, the angle of view (breathing) changes only slightly, thus a very smooth rack focus can be performed. (Fig. 79)
5) Color reproducibility is faithful to the object and the color temperature variation between digital cinema models is small.

Also, a number of techniques exist for evaluating the lens quality of color reproducibility, including one using a vector scope with proven performance for broadcasting lenses, and ISO/CCI commonly used for silver films. (See Fig. 80)

An ISO/CCI-compliant display method of numeric evaluation would be worthwhile to standardize color reproductions, one of the features of digital cinema lenses, in addition to a vector scope approach.

Following extensive evaluations based upon the ISO/CCI techniques, lens materials and associated coatings were optimized to achieve the desired tight consistency in color reproduction between our digital cinema zoom and prime fixed focal length lenses.

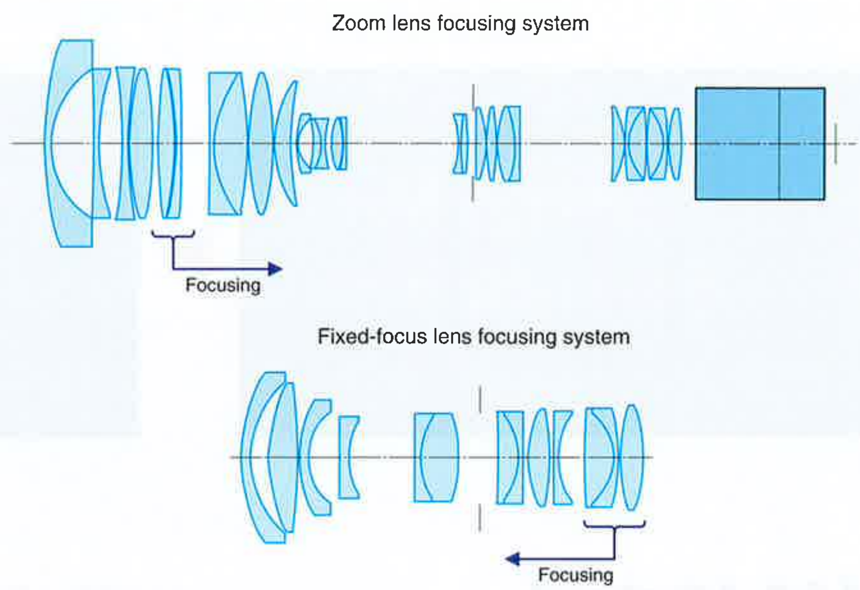


Fig.79 Example of focusing system suppressing the change of angle of view

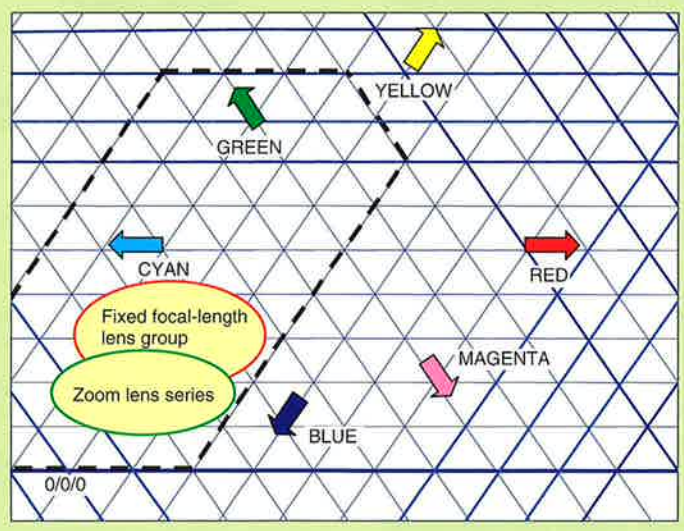
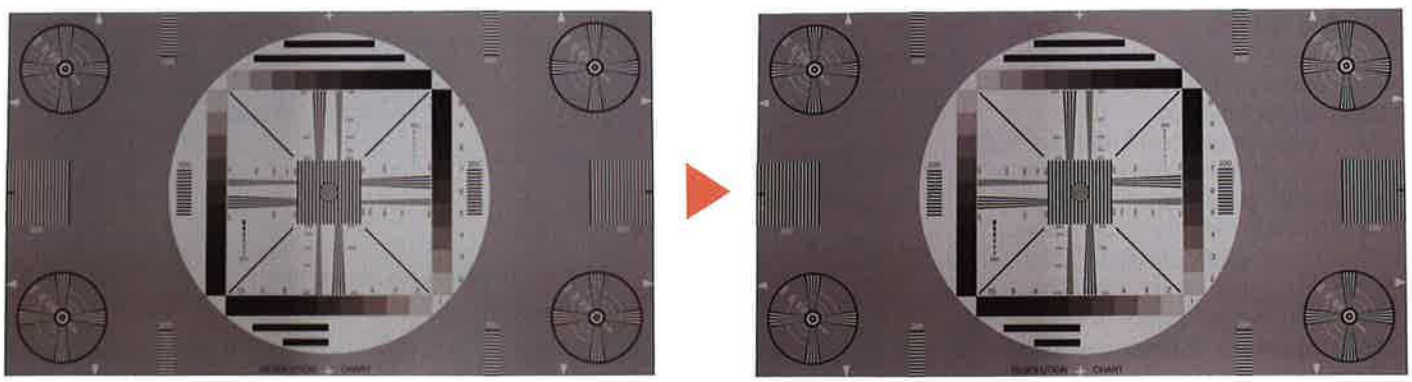


Fig.80 Evaluation by ISO/CCI

5 Using a Zoom Lens Correctly



5.1 F.B. Adjustment

F. B. adjustment is to fit the flange back of a zoom lens to the flange back of a camera. Without this adjustment, the surfaces of the image sensors do not coincide with the correct image plane of the zoom lens, which causes a focus change during zooming. Then the lens does not function as a zoom lens.

The zoom lenses for a TV camera are equipped with the F. B. adjustment mechanism. The mechanism enables the adjustment of a flange back within the range of about ±0.5mm from its standard length by moving some part of the relay lens.

The image plane for the green channel can be made to coincide with the surface of the imaging device by the F. B. adjustment. However, since there are three image planes corresponding to the red, green, and blue channels in a TV camera, the flange backs for the other two channels also have to be adjusted. The adjustment of each channel is called the tracking adjustment.

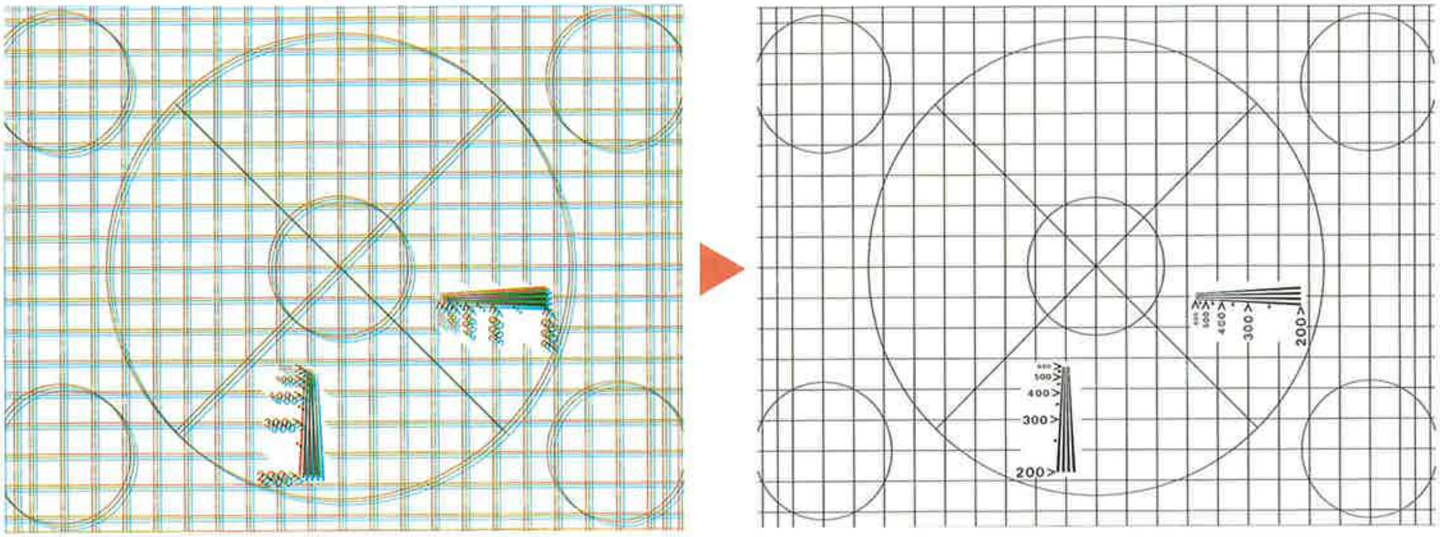
Tracking adjustment is not needed in a CCD camera because the fixation positions of the CCDs are standardized in accordance with the longitudinal chromatic aberration of the lens. (See p. 28.)

Lens Flange-Back Adjustment Procedure

(1) Mount the camera and lenses.
- — Place a siemens star chart*1) at an appropriate distance*2).
  If a chart is not available, use another object with high contrast.
- — Open the lens aperture.
  Adjust the ND filter or other elements, not the aperture, for an appropriate light quantity.

(2) Turn the lens to the telephoto end of the zoom.
(3) Turn the focusing ring to bring the image into focus.
(4) Turn the lens to the wide-angle end of the zoom.
(5) Loosen the lens FB adjustment lock and turn the adjustment ring until the green channel is in sharp focus.
(6) Repeat steps (2) to (5) several times, until the image is in focus at both ends of the zoom.
(7) Turn the lens to the wide-angle end of the zoom and check the focus on the red and blue channels.

Notes:
*1) An appropriate distance is about 3m for a studio or ENG lens, and 5 to 7m for an outdoor lens.
*2) A Siemens star chart has a pattern that becomes finer toward the center, as in the figure, so it is easy to focus on.



5.2 Registration Examination

Registration means aligning the three images formed on the red, green, and blue channels so that they overlap precisely. With a three pick-up tube camera, registration adjustment was necessary before using the camera every time. That was because the registration of the pick-up tube was sometimes influenced by the terrestrial magnetism and changes in temperature.

However, the registration in a CCD camera is so stable that the adjustment is not necessary. In a CCD camera lens, the lateral chromatic aberration is minimized in the entire zoom range from the wide-angle end to the telephoto end. (See p. 29.)

Representation of Registration

The residual lateral chromatic aberration is usually represented in the form of the shift (in microns) on the image plane. However, the shift of the registration are sometimes represented by a TV camera as the time delay of the image signal (in nsec).

A shift of 1 micron on the image plane is converted to nsec as follows:

2/3″........................ 5.9nsec
1/2″........................ 8.2nsec

The shift of the registration is sometimes expressed as a percentage. Generally, the ratio of the shift to the image height is expressed as a percentage.

Recent cameras have an auto-white balance feature with which the entire adjustment can be performed by pressing a single button.

5.3 White Balance Adjustment

A zoom lens consists of many component lenses, so differences in coatings and the absorption coefficient of the glass lead to slight differences in the transmittance.

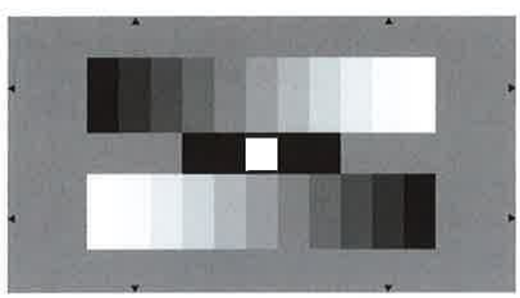
White balance must therefore be readjusted after changing lenses.

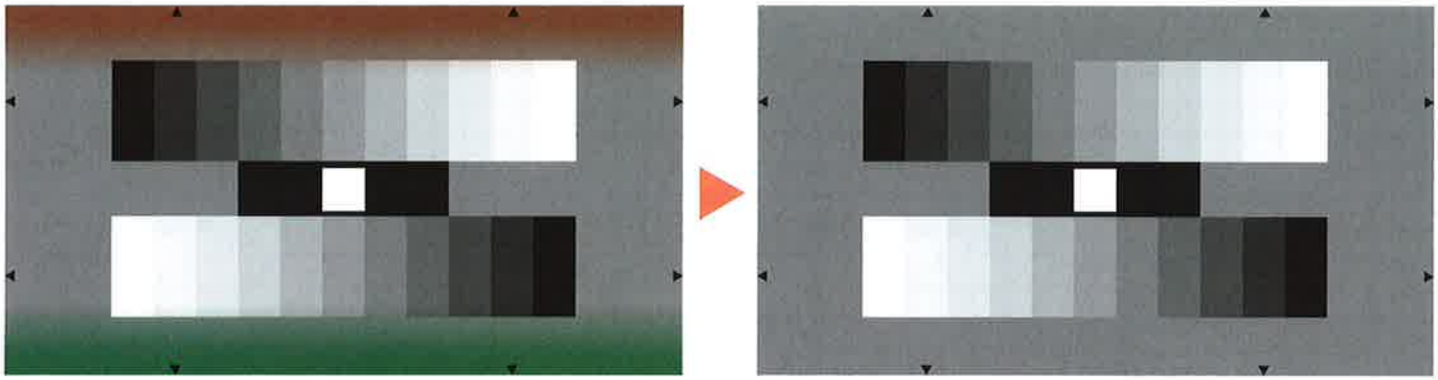
The white balance adjustment procedure is to focus on a white (colorless) object and adjust so that the red, green, and blue outputs are in 1:1:1 ratio.

White Balance Adjustment Procedure

(1) Focus on a gray scale so that it fills the screen. If a gray scale is not available, used a sheet of white paper.

(2) Press the auto-white balance button.





5.4 White Shading Adjustment

In cameras that use a dichroic coating in their color separation system, the coating properties give rise to white shading. (See Section 7.2.) The result is that when the camera is focused on a white subject and the white balance is correct at the center of the image, so that the center looks white, the top and bottom of the image will be out of balance, and will have a magenta or green cast.

The amount of shading is related to the exit pupil of the lens, so white shading has to be readjusted when a lens is replaced by a lens with a different exit pupil distance.

An extender also changes the exit pupil, hence the shading.

5.5 Hints on Focusing

(1) Focus at the telephoto end, then zoom toward wide-angle.

If the lens is first focused on the wide-angle side, then zoomed toward telephoto, focus may be lost, because telephoto focusing is more delicate than wide-angle focusing. A slight deviation from focus that would be unnoticeable on the wide-angle side becomes increasingly apparent as the lens is zoomed toward telephoto.

(2) The focusing ring turns past the ∞ mark.

If the focusing ring of an ordinary film camera is turned all the way toward infinity, it will stop just at the ∞ mark, in which position it is focused on infinity. A telephoto lens with fluorite components however, can be turned slightly past the mark. The refractive index of fluorite changes with temperature more than the refractive index of glass, so if this margin were not allowed, the lens could not be focused to infinity at low temperatures (air temperatures below 0°C, for example).

Television zoom lenses use fluorite lenses to correct chromatic aberration, so like telephoto lenses, they can be turned past infinity.

5.6 Cleaning

Maintenance inspection

Although it depends on how frequently, under what conditions, and in what environment the lens is used, the lens should receive a maintenance inspection about once a year, and an overhaul if necessary. Requests for maintenance inspection can be made to a service agency, or directly to Canon. (Caution: If the lens mechanism or parts have been altered at the user's discretion or the discretion of a third party, Canon may be unable to repair the lens).

Dirt and dust on the lens surface

If there is dirt or dust on the lens surface, it should be removed with an air blower or wiped off gently with a brush. Never wipe the lens hard. A hard wipe can cause dirt to scratch the lens surface.

Oil, fingerprints, and stains

Oil, fingerprints, and similar stains on the lens should be removed by applying a small amount of commercial lens cleaner to a clean, dry, cotton cloth or lens-cleaning paper, and wiping with a circular motion from the center toward the periphery of the lens.

Use in a humid location

The lens is not completely waterproofed. Adequate protection must be given when the lens is used in rain or snow or other conditions in which it is directly exposed to drops of moisture. After the lens is used in a high-humidity environment, any external moisture should be wiped off with a dry cloth, then the lens should be sealed in a vinyl bag with a desiccating agent to remove all moisture from it.

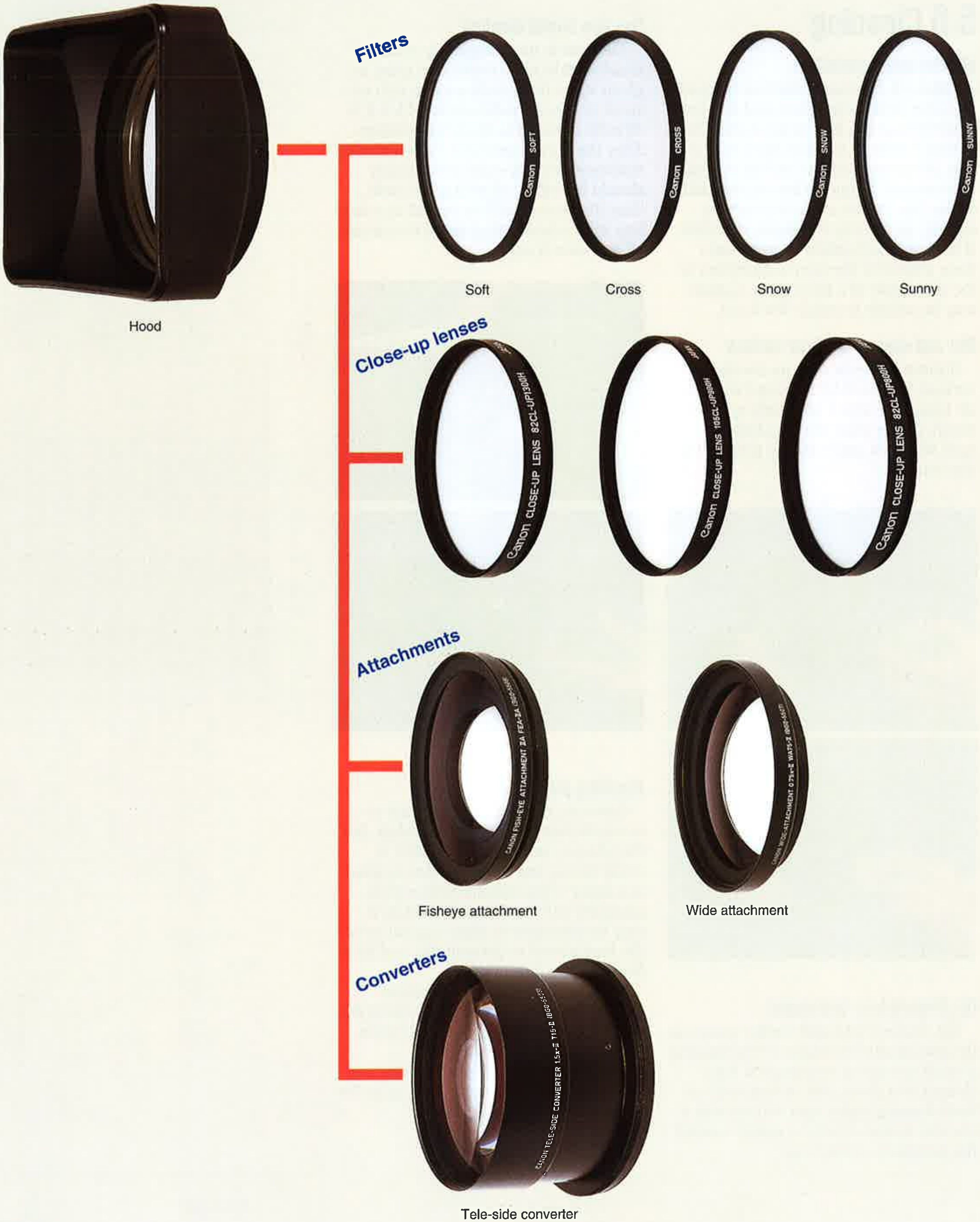
Handling precautions

Careless, rough handling is apt to occur during use or transportation, but the utmost care should be taken to avoid strong impact. If the lens is used in a dusty environment, it should be mounted and demounted quickly. It may be advisable to place a cover over the lens mount to prevent dirt and dust from getting in.

Sudden changes in temperature should be avoided. They may cause the lens to fog internally, making it unusable for a period of time.

Consult Canon before using the lens in a special environment, such as in the presence of chemical vapors.

6 Optical Accessories



UV PL Skylight ND 2 ND 4 ND 8

Extender

Wide converter

6.1 Wide Converter

A wide converter is useful for getting a large number of people into one scene in a narrow space. It shifts the focal length range of the zoom lens in the wide-angle direction, converting it to a more wide-angle lens. If the W80IIA-85II wide converter is attached to the J17e × 7.7B lens, for example, its focal length range shifts from 7.7 ~ 131mm to 6.2 ~ 104.8mm. The F-number remains exactly the same, so the illumination does not have to be changed. The minimum object distance becomes smaller in proportion to the square of the converter magnification, so subjects can be shot closer-up. The lens can still be zoomed through the entire focal length range.

Change in focal length

	Master lens	With wide converter attached
J17e × 7.7B	7.7 ~ 131mm	6.2 ~ 104.8mm
J22e × 7.6B	7.6 ~ 168mm	6.1 ~ 134mm

Changes caused by wide converter
An example in case of J17e × 7.7B

Focal length	0.8 ×
Minimum object distance (magnification)^2 × (Minimum object distance of master lens)	0.38m
Zooming	Usual Operation
F-number	Same as usual

Afocal Converter

An afocal system consists of a convergent lens and divergent lens with the same focal point, as in Fig. 81.

Parallel rays entering the system leave it as parallel rays, so there are no focal points or principal points and no image is formed. The telescopes and finders of still cameras are configured like this.

An afocal system changes the focal length of a taking lens with which it is combined. If rays entering at height h leave at height h', the afocal system has a magnification factor of h/h', and it changes the focal length of the taking lens by this factor.

Because the object point relative the zoom lens does not change even if an afocal converter is mounted on the zoom lens, zooming does not result in a focus shift.

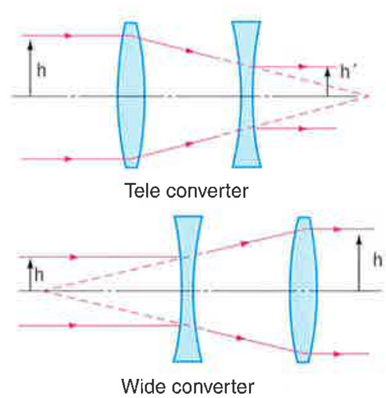


Fig.81 Principle of an afocal converter

6.2 Wide Attachment

A wide attachment is used for the same purpose as a wide converter, but it has a simpler structure.

With a wide attachment, focus is adjusted using the macro mechanism (or the flange-back adjustment feature), so zooming is not possible. The attachment can be used only at the wide-angle end. (If the lens is zoomed, focus is lost.) If the lens does not have a macro mechanism and the focus is adjusted by the flange-back adjustment, the flange-back must be readjusted when the attachment is removed to resume normal shooting.

	Changes caused by attachment	Example: when used with J17e × 7.7B lens
Focal length	Fixed focal length (magnification) × (wide-angle focal length)	Fixed focal length Approx. 5.8mm
Zooming	Not possible	Not possible
Angle of view	Fixed	
Focus adjustment	By macro mechanism	

6.3 Fisheye Attachment

A fisheye attachment is useful for achieving special effects by distorting the image the way a fisheye lens does.

Like the wide attachment, the fisheye attachment can be used only at the wide-angle end, and the focus must be adjusted with the macro mechanism.

With a master lens, the angle of view is:

$$w = 2\tan^{-1}\frac{y'}{2f}$$

A fisheye lens introduces an intentional negative distortion, making the angle of view:

$$w = 4\sin^{-1}\frac{y'}{4f} \quad \text{(Equisolidangle projection)}$$

When the fisheye attachment is used with the J17e × 7.7B lens, the focal length becomes 4.6mm, and the diagonal angle of view becomes 146.9°. Although that is less than 180°, it is enough to permit compositions that would be unattainable with the master lens alone.

Example: J17e × 7.7B with fisheye attachment

Focal length	4.6mm, fixed focal length
Zooming	Not possible
Focus adjustment	By macro mechanism
Angle of view	114.3° × 84.1° diagonal 146.9°

6.4 Tele-Side Converter

A tele-side converter attached in front of a zoom lens shifts its focal length range in the telephoto direction, converting it to a more telephoto lens with greater reach. For example, the T15II-85 tele-side converter converts the focal length range of the J17e × 7.7B lens (which is 7.7 ~ 131mm) by a factor of 1.5, making the maximum focal length 196.5mm.

A tele-side converter does not have the F-drop that occurs when the internal extender is inserted. The F-number remains exactly the same as with the master lens alone.

A tele-side converter is designed to be used only on the telephoto side of the zoom, however. If the lens is zoomed to the wide-angle side, the converter diameter would have to be so large that the camera would become unwieldy. That is the reason for the word "side" in the name "tele-side." With a T15II-85 tele-side converter on a J17e × 7.7B lens, peripheral eclipse occurs from about f = 60mm down to the wide-angle end, making this part of the range unusable.

The minimum object distance changes in proportion to the square of the magnification factor. For the J17e × 7.7B and T15II-85 combination, for example, it changes from 0.6m to 1.35m.

*Minimum object distance = (magnification factor of tele converter)^2 × (minimum object distance of master lens)

(J17e × 7.7B) + (T15-85)	1.3m
(J22e × 7.6B) + (T15II-85)	1.8m
(HJ22ex × 7.6B) + (T15HD-98II)	1.9m

6.5 Extender

An extender is the accessory that brings in enlarged, close-up, shots of players' faces in live sports broadcasts. It is mounted between the camera and the lens to enlarge the image of the subject, or shoot more distant subjects. It increases the focal length of the master lens, making it into a more telephoto lens.

Inserting a 2.0× extender into a J17e × 7.7B lens, for example, changes the focal length range from 7.7 ~ 131mm to 15.4 ~ 262mm. An extender also multiplies the F-number by the same amount, however. The 2× extender doubles the F-number, leaving only 1/4 the speed, the same as if the lens aperture were stopped down to half its diameter. The reason is that the focal length is doubled without changing the lens diameter.

Example of J17e × 7.7B with extender

	Master Lens	With extender
Focal length	7.7 ~ 131mm	15.4 ~ 262mm
F-number	1.8 ~ 2.3	3.6 ~ 4.6
Lens speed (relative value)	1	1/4

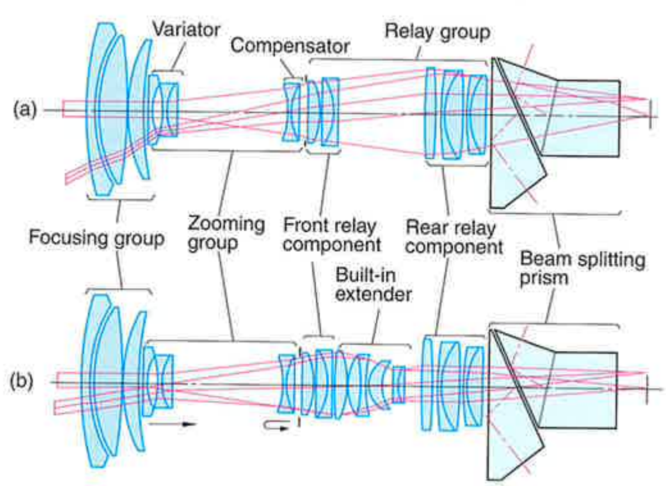
Built-in Extender

Since extenders are useful and are frequently used, many zoom lenses now have them built in. (Fig. 82)

A large studio lens may have two or three built-in extenders, giving the cameraman versatile lens-work options.

A built-in extender can be thought of as an adaption of the afocal converter.

Accuracy was formerly a serious problem with built-in extenders, but production technology has improved and their performance is now very high.



(a) System without built-in extender
(b) System with built-in extender

Fig.82 Zoom lens with built-in extender

6.6 Close-Up Lens

A close-up lens is effective for close-up photography of, for example, flowers and insects.

If the 82CL-UP1300H close-up lens is mounted in front of the J17e × 7.7B lens, when the focusing ring is turned to ∞, the lens is actually focused on a distance of 1.3m. When the focusing ring is turned to the minimum object distance of 0.6m, the actual focusing distance is 0.4m.

At a focusing distance of 0.4m the object dimensions to fill the image format is 411mm × 308mm, so the screen is filled by a subject about the size of a 35mm side. Focusing becomes difficult, because the depth of field is extremely shallow. The lens should be stopped down as far as possible.

In principle, a close-up lens is a single convex lens. If the focal length (fc) of the close-up lens is 1300mm, then a subject placed at the object focal point (1.3m from the lens) will be focused by the close-up lens to form an image at infinity, which the zoom lens can shoot if the focusing ring is turned to the ∞ mark. (Fig. 83)

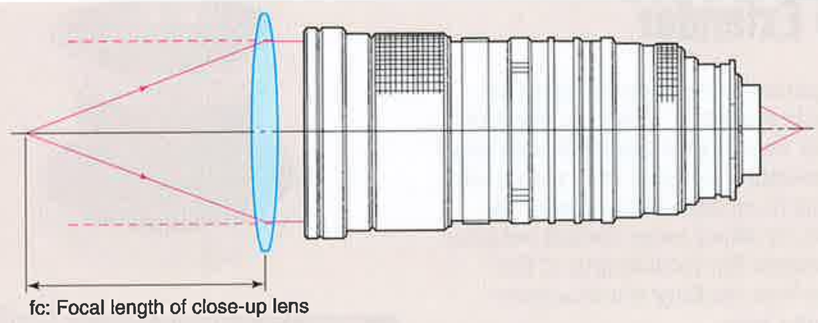


Fig.83 Principle of close-up lens

Relation between Object Dimensions and Object Distance

(1) When focusing ring of lens is turned to infinity

f: Focal length of lens

fc: Focal length of close-up lens

Object distance = fc

Magnification M = f/fc

Object dimensions = (1/M) × (image size on CCD)

(2) When focusing ring of lens is turned to finite value

S: Distance setting on focusing ring

f_1: Focal length of focusing lens

$$\text{Object distance} = \frac{fcS}{S + fc}$$

m_2: Magnification due to close-up lens

m_3: Magnification due to zoom lens

$$m_2 = \frac{S}{fc} + 1 \qquad m_3 = \frac{f}{S - f_1}$$

Magnification

$$M = m_2 \cdot m_3 = \left(\frac{S}{fc} + 1\right)\left(\frac{f}{S - f_1}\right)$$

When object distance is enough so $f_1 < S$

$$M \doteqdot \left(\frac{S}{fc} + 1\right)\frac{f}{S}$$

Object dimensions = (1/M) × (image size on CCD)

■Imaging range for J17e × and HJ17e × with close-up lens

	Close-up 800mm (82CL-UP800H 1sheet)				Close-up 1300mm (82CL-UP1300H 1sheet)			
J17e × 7.7B (mm)	131		7.7		131		7.7	
(Focusing scale) (m)	∞	0.6	∞	0.6	∞	0.6	∞	0.6
(Object distance) (m)	0.8	0.34	0.8	0.34	1.3	0.4	1.3	0.4
Imaging range (mm)	53×40	21×16	908×681	341×256	87×65	25×19	1499×1124	411×308

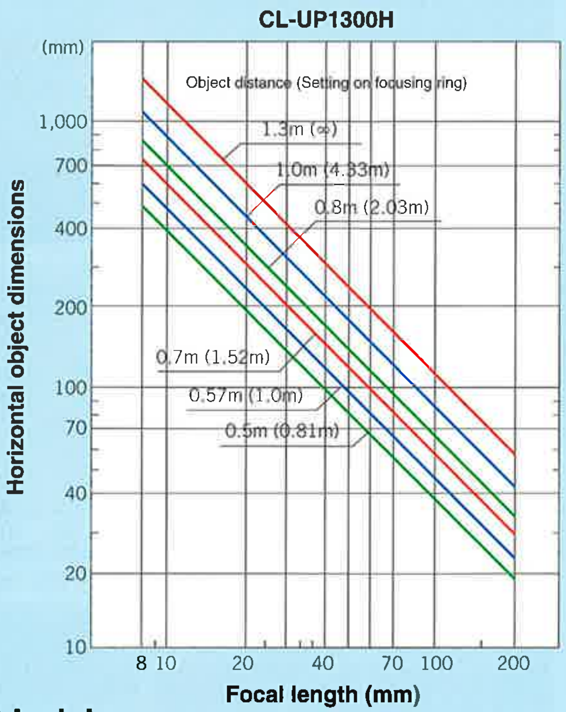
	Close-up 800mm(HD) (105CL-UP800HD 1sheet)			
HJ17e × 7.7B (mm)	131		7.7	
(Focusing scale) (m)	∞	0.75	∞	0.75
(Object distance) (m)	0.8	0.38	0.8	0.38
Imaging range (mm)	58×33	27×15	1000×563	446×251

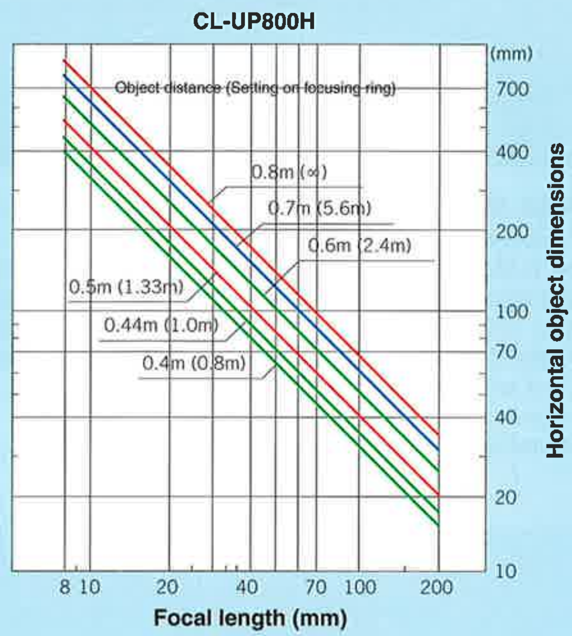
The approximate field size when using a close-up lens can be obtained with the graph shown below.

There is not much difference in the field size of different lenses with the same focal length.

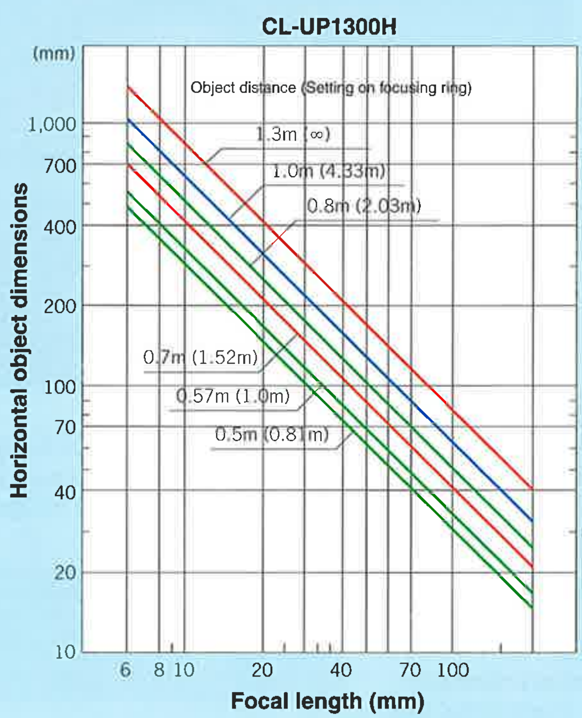
When detailed objects such as documents are focused on at a short distance, problems such as lateral chromatic aberration become noticeable. It is therefore better to avoid using a telephoto end for focusing at short distances. With the use of a close-up lens, the same object dimensions can be obtained at a middle focal length.

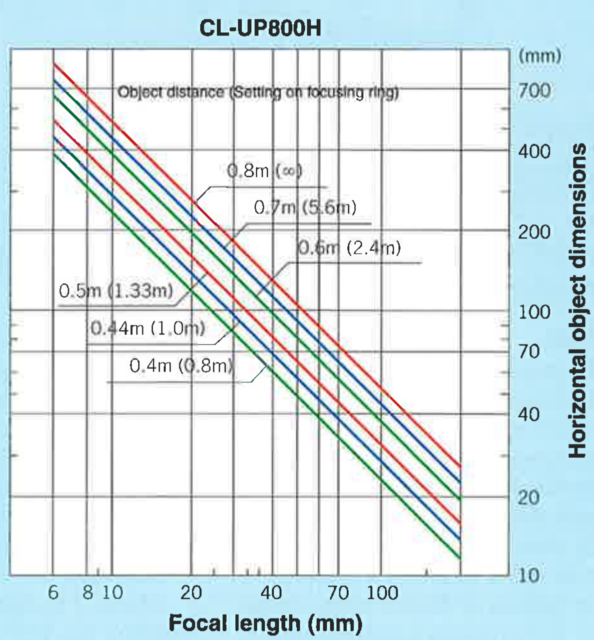
2/3-Inch Lens





1/2-Inch Lens





6.7 Optical Filters

(1) UV filter, skylight filter

A UV (ultraviolet) filter is nearly colorless. It absorbs short-wavelength ultraviolet rays that the naked eye cannot see. (Fig. 84)

A skylight filter has a light pinkish color. Used when shooting on clear days, it removes ultraviolet, and prevents natural light from giving a bluish-green cast to shaped foliage etc.

A zoom lens contains so many lens components that almost all ultraviolet light is absorbed inside the lens.

A filter is still advisable to protect the front lens surface, however.

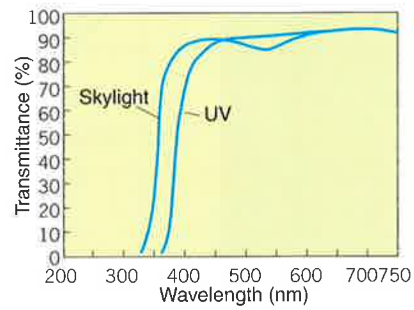


Fig.84 Transmittance of UV fillter and skylight filter

(2) ND filter

An ND (neutral density) filter uniformly reduces light of all wavelengths which enters a lens.

It is used when the subject is too bright for the light to be adjusted by the diaphragm alone.

An ND filter can be used to control the light in order to shoot a subject such as a person or flower with a large aperture. This creates a shallow depth of field, making the subject's beauty stand out against the defocused background, and emphasizing the impression of three dimensions.

The strength of an ND filter may be expressed as a density D, transmittance T, or exposure factor. These parameters are related as follows.

Density $D = -\log_{10}T$

Exposure factor $= 1/T$

where T is expressed as a decimal fraction (so 100% = 1). Commercial film lens filters are usually specified by the exposure factor.

A dense ND filter absorbs light a little more strongly at shorter wavelength, so it may necessitate white balance readjustment.

ND filter type	Transmittance	Density
ND2	50%	0.3
ND4	25%	0.6
ND8	12.5%	0.9

(3) Color conversion filters

These are also called CC filters.

Color temperature expresses the balance of colors of a light source. It refers to the color radiated by a perfectly black body when heated. A low color temperature is reddish. As the color temperature rises, the color changes to yellow, then blue.

An amber filter reduces the color temperature, while a blue filter raises the color temperature. Television cameras are designed for the standard illumination in a television studio, which has a color temperature of 3000K to 3200K, so an amber filter is necessary for outdoor shooting.

The color conversion capability of a CC filter is measured in mired (micro reciprocal degree: 1,000,000 divided by the Kelvin temperature) or decamired (10 mireds) units.

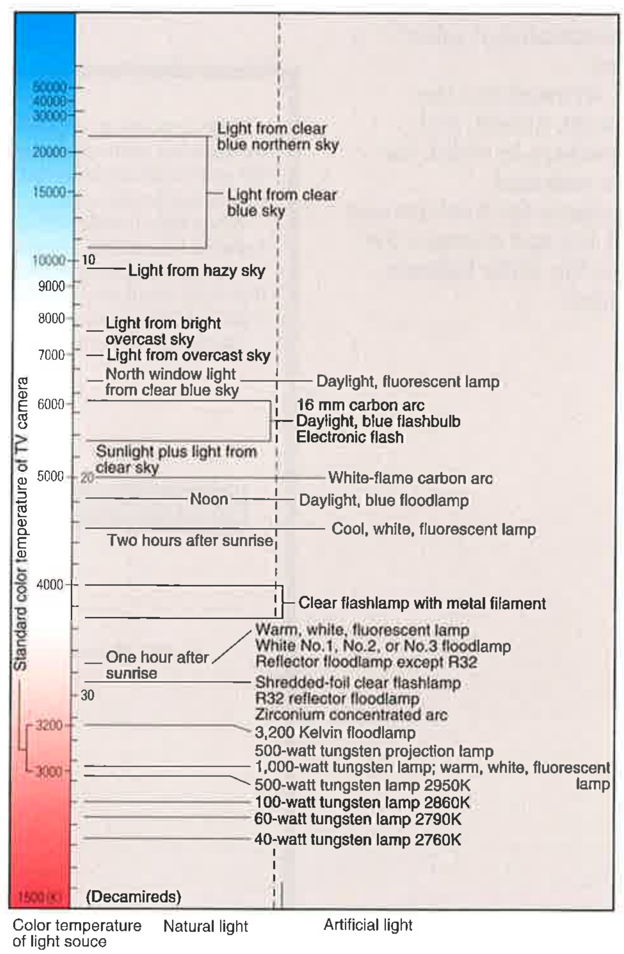
A filter that converts a color temperature T_1 to a color temperature T_2 has a decamired value of:

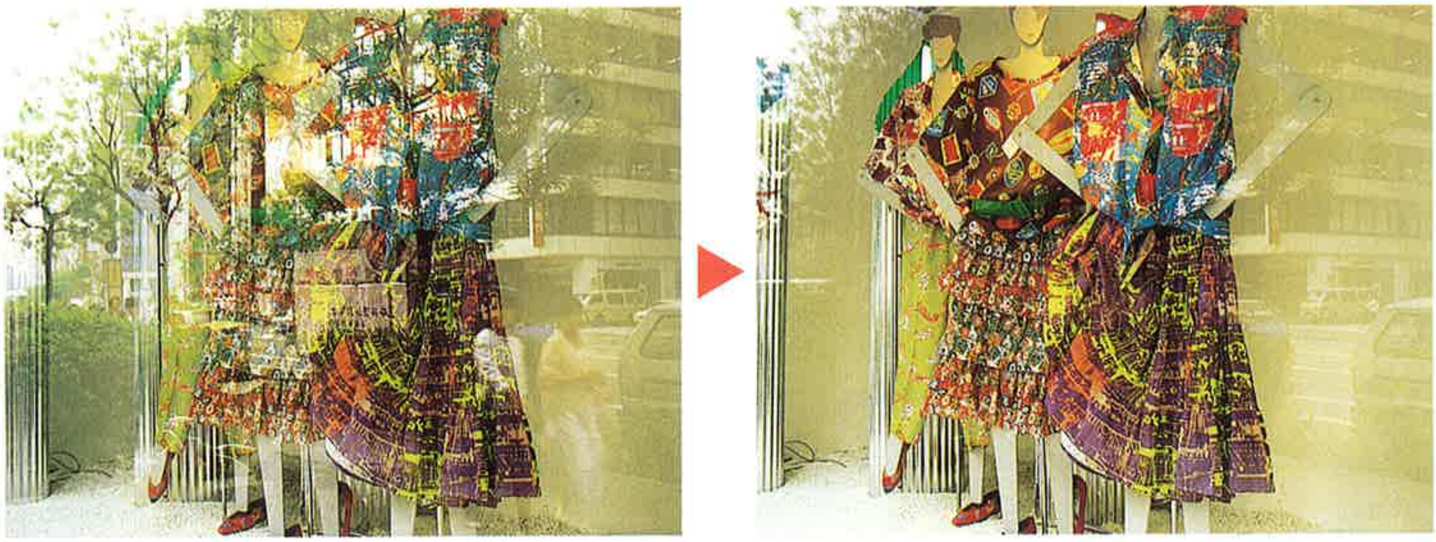
$$\frac{100000}{T_1} - \frac{100000}{T_2}$$

A hand-held camera usually has two internal CC filters: a 16 decamired filter to convert the color temperature of sunlight (5600K) to 3000K, and a 10 decamired filter to convert the color temperature of fluorescent illumination (4300K) to 3000K.

Color Temperatures for Various Illumination

To find the decamired value of the correct filter to use, read the decamired value of the illumination from the chart below, and subtract the decamired value of the standard color temperature of the TV camera (33.3 if the standard color temperature is 3000K, or 31.3 if it is 3200K).





(4) Polarizer

A polarizer is used to intercept light reflected from the surface of water of glass.

Since light scattered by the atmosphere is partly polarized, a polarizer is also effective when shooting subjects aginst a blue sky. It can suppress the sky and make mountains or other objects stand out.

A polarizer is screwed into the threads of the hood, turned, and stopped in the position in which the reflected light is removed.

A polarizer reduces the total amount of light to about 1/4 and changes the color balance, so the white balance must be readjusted.

Polarization

Light consists of transverse waves which oscillate in a particular plane. In natural light the planes are oriented randomly, so no polarization can be detected.

When light is reflected at an interface between two media, however, light oscillating in some planes is reflected more strongly than light oscillating in other planes, so the reflected light is polarized.

The polarized component oscillating in the plane of incidence is called P polarized light. The polarized component oscillating perpendicular to the plane of incidence is called S polarized light (S stands for 'senkrecht' in German.).

Reflected light contains a stronger S component. (Fig. 86)

A polarizer transmits only one linearly polarized component. (Fig. 87)

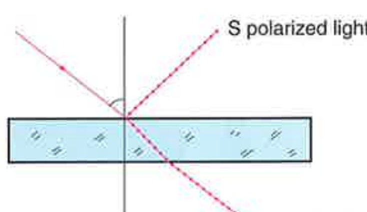


Fig.85 Polarization of reflected light

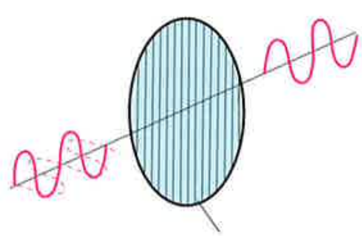


Fig.87 Polarizer

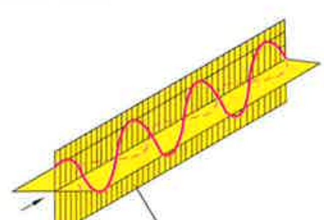


Fig.86 Principle of polarization

(5) Soft-focus filter

A soft-focus filter has a mat-like surface that imparts a soft, misty effect to the entire picture.

Soft-focus filters are frequently used for lyric scenery shots.

(6) Cross filter

A cross filter creates a cross or star of light by scattering rays from a strong light source in the subject in a radial pattern. The brighter and more point-like the subject is, the better the effect is. Cross filters are often used to enhance night scenery or stage show broadcast.

***Types of cross filter**

—Cross filter: Scatters light in a four-pointed cross

—Snow cross filter: Scatters light in a six-pointed star

—Sunny cross filter: Scatters light in an eight-pointed star

Without filter


With snow cross filter


With cross filter


With sunny cross filter

7 Color Separation Optical System

7.1 Configuration of Color Separation Optical System

A color television camera contains an optical system that separates light into its component colors. This system is of key importance: besides determining the faithfulness with which the camera reproduces color, it influences the arrangement of the image pick-up devices, and therefore the camera design itself.

Most modern broadcast cameras used an arrangement of prisms. (Fig. 88)

A trimming filter is located at the exit of each prism to eliminate unwanted light and improve color reproduction.

Most arrangements have a color conversion filter and an ND filter, replaceable using a turret, set up in front of the prism, with a crystal filter in the foreground. The crystal low-pass filter has an IR cutoff filter being integrated into it.

As was pointed out in Section 2.8, a camera that uses this type of prism system requires a special zoom lens that is corrected for the prism system.

As can be seen from Fig.88, the beam-splitting prisms make ingenious use of selective reflection at dichroic layers and total reflection to separate incident light into its three consituent colors.

A dichroic layer is formed by vacuum evaporation of several tens of layers with alternating high and low refractive indices. Proper choice of the material and thickness can give the dichroic layer the property of reflecting only one color and passing other colors through. (Fig. 89)

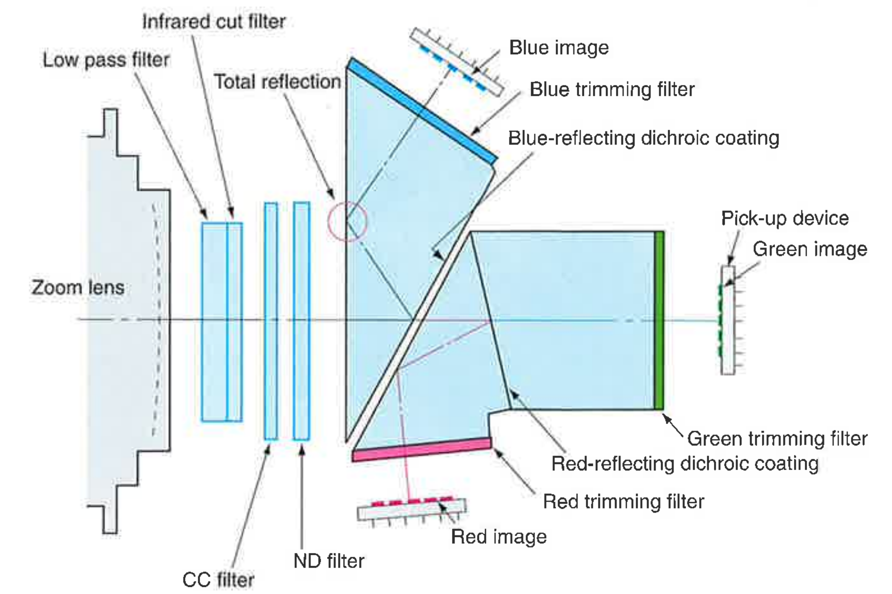


Fig.88 Color separation optical system of a TV broadcast camera

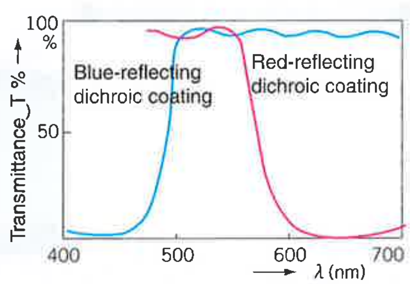


Fig.89 Transmittance of dichroic coatings

Prisms for HDTV Cameras

The performance required for the HDTV system is more than twice that required for the conventional system. And the matching between the lens and the prism is important to use the lens at maximum performance. For this reason, the standardization for the prism is included in the camera/lens interface standard.

Since the shift in chromatic aberrations greatly influences the optical performance in an HD system, the material and the thickness of a prism are standardized.

High accuracy is required in the manufacturing of prisms. That is because the accuracy of the surface and angle influence the MTF.

Lens mounts and electrical interfaces lacking in compatibility among camera makers used to stir user confusion. In an HDTV system, however, compatibility is ensured by setting a standard in the first place, which benefits the user.

■Specification for 2/3″ type HDTV camera optical interface

Offset in focusplanes	R-G: +10μm B-G: +5μm
Glasslength	46.2 ± 0.5mm Glass 1 : Refractive index 1.52 to 1.75 Standard value 1.612 (BaF52*) Abbe number 46.5 ± 4.0 Glasslength 33.0 ± 4mm Glass 2 : Equivalent of BK7 Glasslength 13.2 ± 4 mm
Flange back	48.0 ± 0.01mm in air

* BaF52 is a registered trademark of SCHOTT AG.

7.2 Spectral Characteristics

The special characteristics of the prisms are the determining factor in the quality of color reproduction achieved by the camera.

Figure 90 shows the typical spectral characteristic of a blue-reflecting dichroic coating.

Dichroic coatings do not transmit 100% of the light even in their passing wavelength range, but some proportion of reflections is left. This residual needs to be cut with trimming filters, because it could mix with other color channels to detract color reproducibility. The trimming filters also reshape the spectral characteristics to improve the reproduction of neutral colors.

Figure 91 shows an example of the spectral characteristics of an entire color separation system.

The physical properties of the dichroic coatings used in the color separation system give rise to three unwanted effects, described next.

(1) White shading

Due to differences in the angle of incident light on the dichroic coatings, when the white balance is correct at the center of the image, the upper and lower edges may have a magenta or green cast. (Fig. 92)

A dichroic coating exploits the interference of light. Different angles of incidence result in different light paths in a multilayer coating, causing variations in the color separation characteristic. As a general rule, the larger the angle of incidence, the more the characteristic is shifted in the short-wavelength direction. (Fig. 93)

A pencil of rays exiting from a zoom lens diverges from a point on the exit pupil, so the rays directed toward the upper and lower edges of the image strike the dichroic coating at different angles, as can be seen in Fig. 94. The resulting differences in characteristics shade the upper and lower edges of the image toward magenta or green.

Due to vignetting, when the lens is zoomed or stopped down, the exit pupil

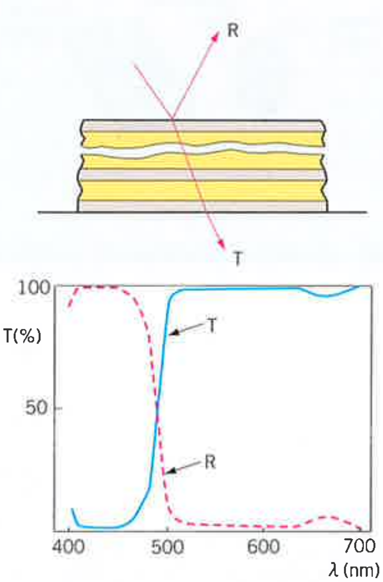


Fig.90 Transmittance-reflectance characteristic of blue-reflecting dichroic coating

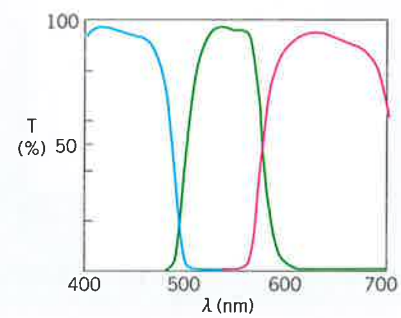


Fig.91 Spectral characteristics of an entire color separation prism

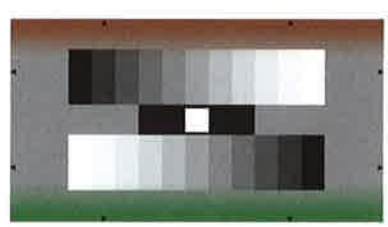


Fig.92 White shading effect

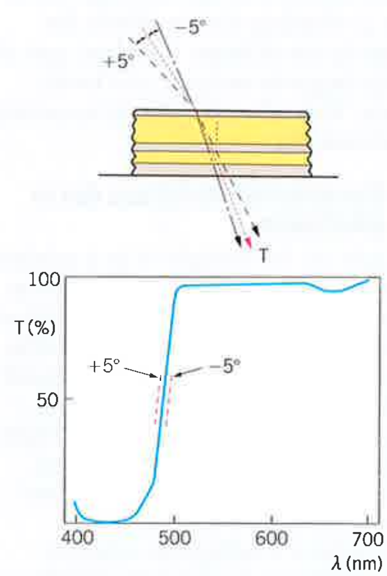
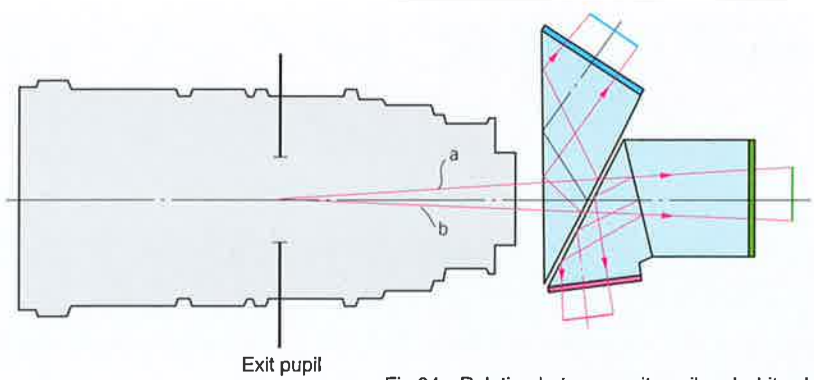


Fig.93 Incidence characteristic of a blue-reflecting dichroic coating



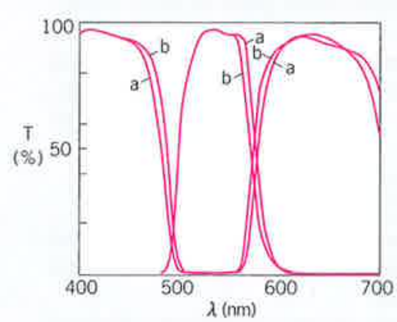


Fig.94 Relation between exit pupil and white shading

changes slightly, causing changes in the shading. Use of an extender also causes shading effects by changing the exit pupil.

White shading can be eliminated electronically within the camera.

(2) Color shading of defocused images

This effect is not present when the image is in focus, but when the subject has depth, so that part of it is defocused, the colors of the defocused part are shaded in the vertical direction. (Fig. 95)

As with white shading, the cause is the difference in spectral characteristics at different angles of incidence on the dichroic coating.

Because rays *a* and *b* strike the dichroic coating at different angles, ray *a* is transmitted as green light and ray *b* as closer to magenta. When the image is in focus, both rays arrive at the same point, and their colors average out so that no shading occurs. When the image is out of focus, however, part of it looks magenta and part of it looks green. This effect is difficult to correct electronically.

(3) Characteristic variations due to polarization

Light can be thought of as a mixture of transverse waves, some oscillating perpendicular to the plane of incidence (S components) and some oscillating parallel to it (P components). Natural light contains equal proportions of S-polarized light and P-polarized light. Light reflected on a glossy subject, such as a glass surface or water surface, makes polarized light.

A dichroic coating has different characteristics for S polarized light and P polarized light. The color of polarized light is therefore different from its original. (Fig. 96)

This effect can be prevented by placing a quarter-wave plate in front of the prism to change the plane polarization of incident light to circular polarization.

Quartz filters are used as $\lambda/4$ plates, but they have a disadvantage of a high material cost (Fig. 97).

As modern cameras continue to feature CCDs, they tend to have a crystal low-pass filter arranged in front of their prism assembly to produce the $\lambda/4$ effect.

This can almost completely eliminate the polarization effect.

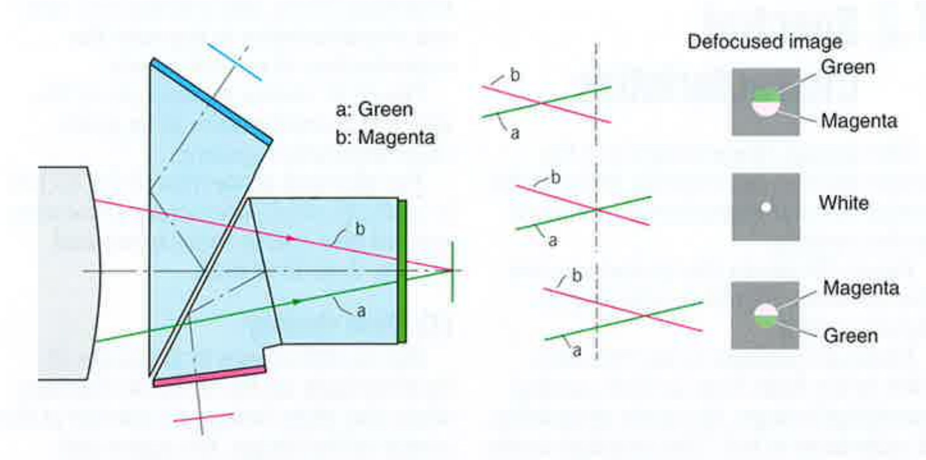


Fig.95 Principle behind color shading of defocused image

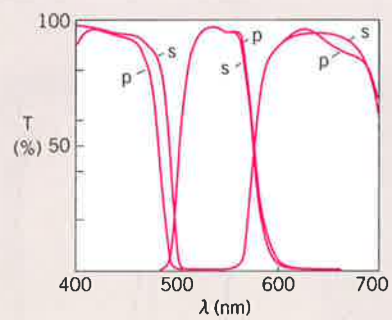


Fig.96 Polarization characteristics of color separation prism

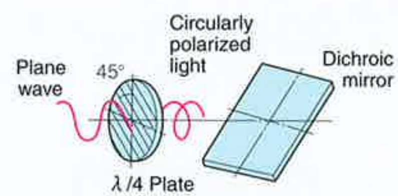


Fig.97 Correction of polarization by a quartz filter

Using $\lambda/4$ Plate to Correct Polarized Light

A quarter-wave plate has an internal optic axis. It generates a quarter-wave phase difference between light polarized in the plane parallel to the optic axis and light polarized in the plane perpendicular to the optic axis.

Circularly polarized light can be thought of as a composition of two components that are polarized in perpendicular planes and are one-quarter wavelength out of phase. A quarter-wave plate therefore has the following properties:

(1) It changes circularly polarized light to light polarized in a plane 45° to its optic axis.
(2) It changes light polarized in a plane 45° to its optic axis into circularly polarized light. (See Fig. 98)

A quartz plate is double-refractive, with different indices of refraction for ordinary rays and extraordinary rays. If the refractive index for ordinary rays is *no*, the refractive index for extraordinary rays is *ne*, and the thickness of the quartz plate is *d*, then the plate is a quarter-wave plate for wavelengths λ satisfying the equation:

$$(N + \frac{1}{4})\lambda = (no - ne)d$$

$no = 1.5443$
$ne = 1.5534$
N: integer

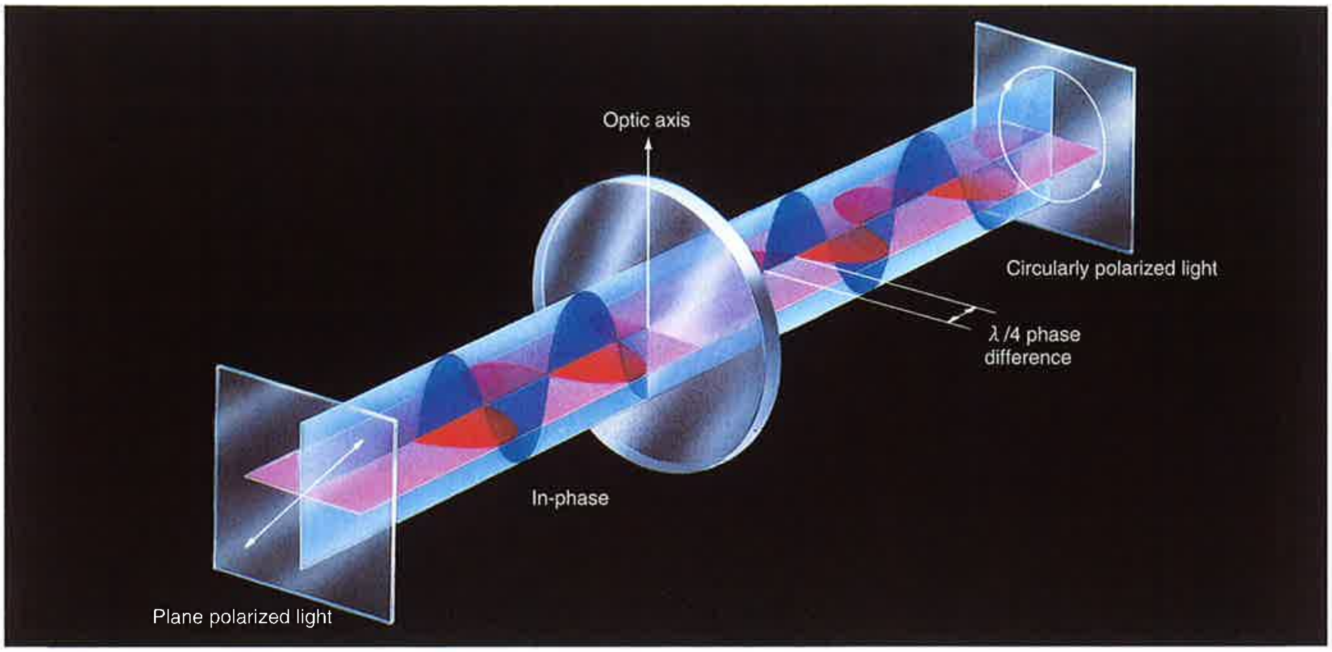


Fig.98 Function of a quarter-wave plate

7.3 Low Pass Filter

CCD chips have all their light sensitive spots (pixels) lined up regularly, and the image signal is obtained by sampling the optical image in two dimensions. However, the sampling sometimes causes Moire patterns which result in a spurious signal when the picture of a detailed object is taken.

Figure 99 (a) shows black and white grids superimposed over the pixels in the CCD. Figure 99 (b) shows the output signal of the CCD. Despite the presence of three black lines for five pixels in (a), only two black lines are noticeable in the output signal. A signal that gives the appearance of an output different from a pattern is called a "spurious signal," in which spatial frequencies in the image appear in a frequency region higher than twice the

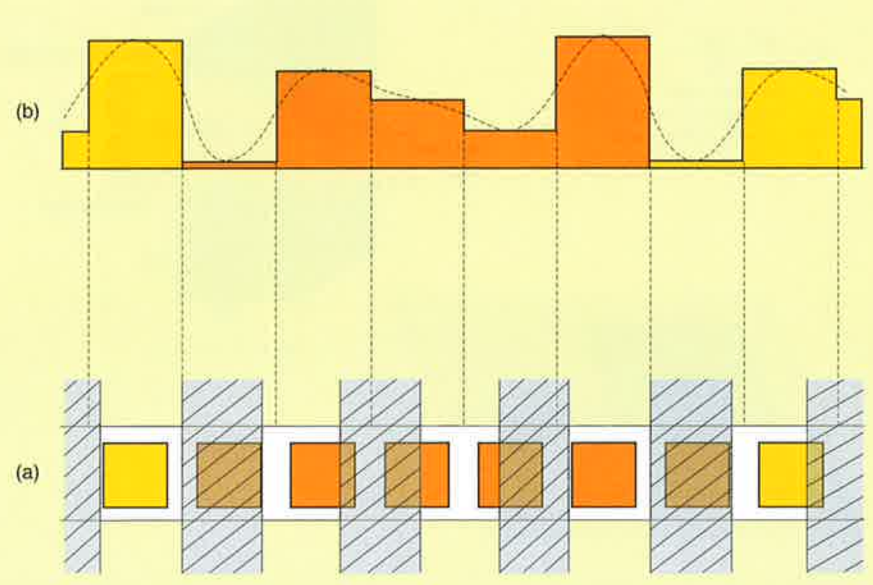


Fig.99 Aliasing by sampling

pixel pitch.

To eliminate this problem, an optical low pass filter is set between the lens and the prism. Optical low-pass filters come in several variations. Among them, a low-pass filter that works on the principle of crystal double refraction (see Figs. 100 and 101) is introduced here. Its principles of operation are illustrated in Figure 102. Suppose that a pattern whose spatial frequency is twice that of the pixel cycle is projected. When this pattern goes through a crystal plate whose separation width is the same as the pixel cycle, the separated images overlap on the CCD, with no pattern projected. Therefore it does not cause a spurious signal.

Although low pass filters eliminate spurious signals, they reduce the resolving power. The characteristics of the low pass filter are determined considering the balance between the prevention of spurious signals and the loss in resolution.

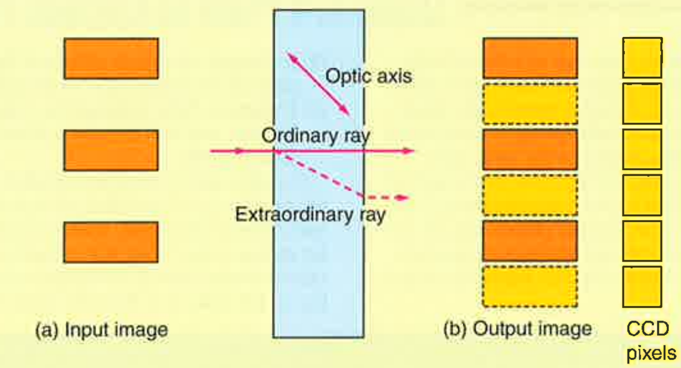


Fig.102 Crystal low pass filter

7.4 Color Reproducibility

Color is a subjective property. To treat it quantitatively, it is expressed in coordinates on a chromaticity diagram.

If $I(\lambda)$ is the intensity of light at wavelength λ received from an object, the coordinates of the object on an x-y chromaticity diagram are found as follows:

$$X = \int I(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = \int I(\lambda)\bar{y}(\lambda)d\lambda$$
$$Z = \int I(\lambda)\bar{z}(\lambda)d\lambda$$

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z}$$

The functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the international standard tristimulus functions shown in Fig. 104, which represent average values derived from measurements on a large number of human subjects.

In the CIE x-y coordinate system that uses these x and y coordinates, the distance between two points does not correspond to human perceptions of color difference. (Fig. 105) To obtain distances that match human perceptions, a transformation of coordinates to uniform chromaticity scale (UCS) is required. The u-v chromaticity coordinate system is an approximate type of UCS coordinate system. (Fig.106)

The transformation from x-y to u-v coordinates has the following equations:

$$u = \frac{2x}{6y - x + 3/2} \quad v = \frac{3y}{6y - x + 3/2}$$

In u-v coordinates, the ellipses of discrimination are all about the same

Double Refraction

The phenomenon where a light flux is separated into two when passing through some crystal (Fig. 100) is a well known phenomenon occurring in calcite or the like. Quartz crystal is example. When the optic axis of a crystal is not parallel to the normal line of the crystal surface, as shown in Fig. 101, the incident ray, even if it is perpendicular to the surface, is split into two. One is refracted at the surface and changes direction in the crystal, and the other does not change direction. The former is called an extraordinary ray because it does not obey Snell's law of refraction, and the latter is called an ordinary ray. The separation of the rays can be varied by changing the thickness of the crystal.

$$d = \frac{No^2 - Ne^2}{2 \cdot No \cdot Ne} \cdot t$$

d: Separate width
t: Thickness of quartz
No: Index of ordinary rays
Ne: Index of extraordinary rays

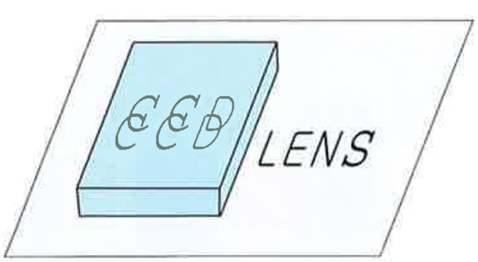


Fig.100

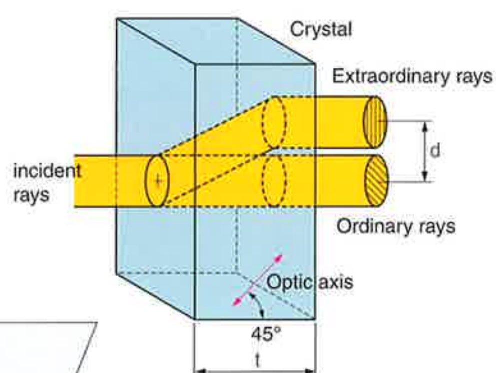


Fig.101

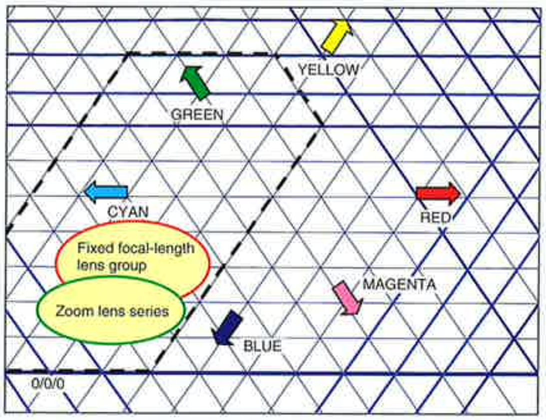


Fig.103 Evaluation by ISO/CCI

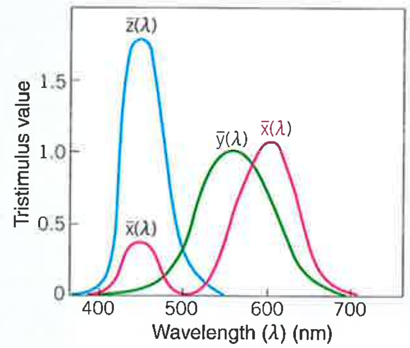


Fig.104 Tristimulus functions

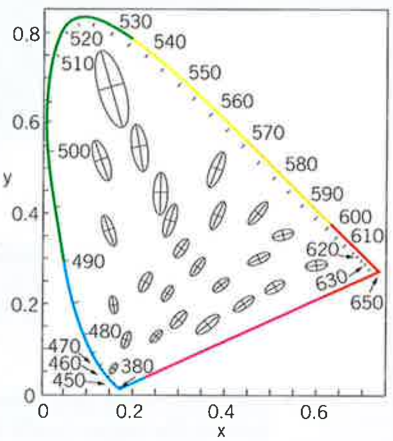


Fig.105 x-y Coordinate system

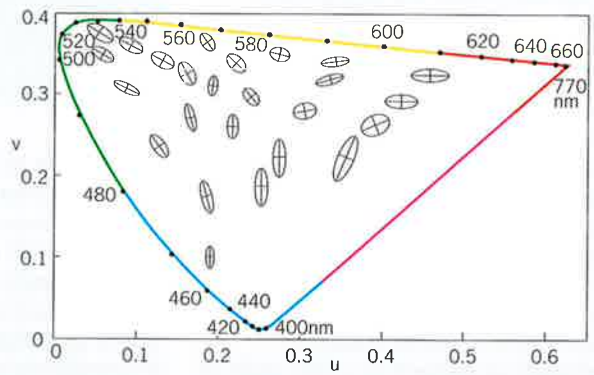


Fig.106 u-v Coordinate system

size.

Figure 107 shows a computed simulation of the colors of an object and its image on a television monitor, plotted in u-v coordinates.

In the simulation, the color of the object is its color under illumination by a D_{65} light source. The image color is as reproduced to D_{65} while shooting a subject illuminated at 3200K. (Fig. 107)

If a linear matrix circuit is used in the camera, the reproduced colors can be matched fairly precisely to the color of the subject. (Fig. 108)

Vector scopes and other instruments are also used to make field checks.

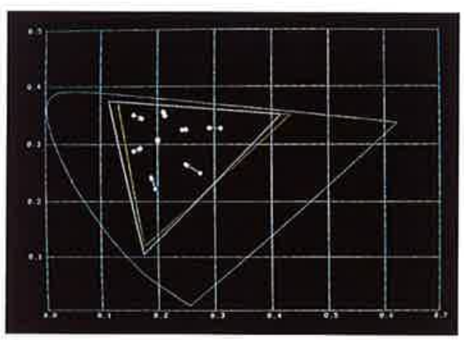


Fig.107 Chromaticity diagram of reproduced color

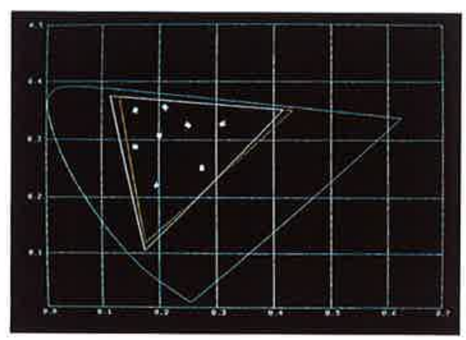


Fig.108 Result of linear matrix

7.5 The F-Number of a Prism

Since a prism has no focusing effect, it has no real F-number, but it is still common to speak of a beam-splitting (color separation) prism as being F1.6, say, or F1.4.

An F1.4 beam-splitting prism is a prism that will separate colors correctly when the incoming light is focused by an F1.4 lens.

The color separation prism of the 3CCD color camera for broadcasting consists of three pieces as shown in Fig. 109. After passing through the lens, the rays enter the first prism, which has a dichroic coating that reflects only blue light. The reflected blue light undergoes a further total reflection at surface 1, then forms the blue channel image.

The red and green light that passes through the blue-reflecting dichroic coating enters the second prism, where it is separated into red and green components by a red-reflecting dichroic coating. These components form the red-and green-channel images.

The angle of surface ②—the angle at the vertex of the first prism—is determined by the F-number of the lens and the refractive index of the prism glass. The requirement that all blue light be reflected internally at surface ① places a lower limit on the vertex angle. The requirement that light other than blue be transmitted at surface ② places an upper limit on the vertex angle. The smaller the lens F-number, the larger the lower limit is and the smaller the upper limit is.

As the F-number of the lens is made smaller, there comes a point where the upper and lower limits of the vertex angle are the same. The F-number cannot be reduced further. This F-number limit occurs at F1.4, and varies only slightly with the refractive index of the prism glass. Thus, the 3-piece color separation prism can attain the aperture of up to F1.4.

Figure 109 also indicates what happens if a brighter lens, such as an F1.2 lens, is fitted to an F1.4 beam-splitting prism. If the rays incident at Ⓐ, the blue light is reflected from surface ② back to surface ①, but because of the small angle of incidence at surface ①, total reflection does not occur and some of the light escapes to the outside, Rays entering at Ⓑ strike surface ② at too large an angle—more than the angle of total internal reflection—so red and green light that should be transmitted is completely reflected and fails to reach the red and green channels.

These problems affect white shading and color shading of defocused images.

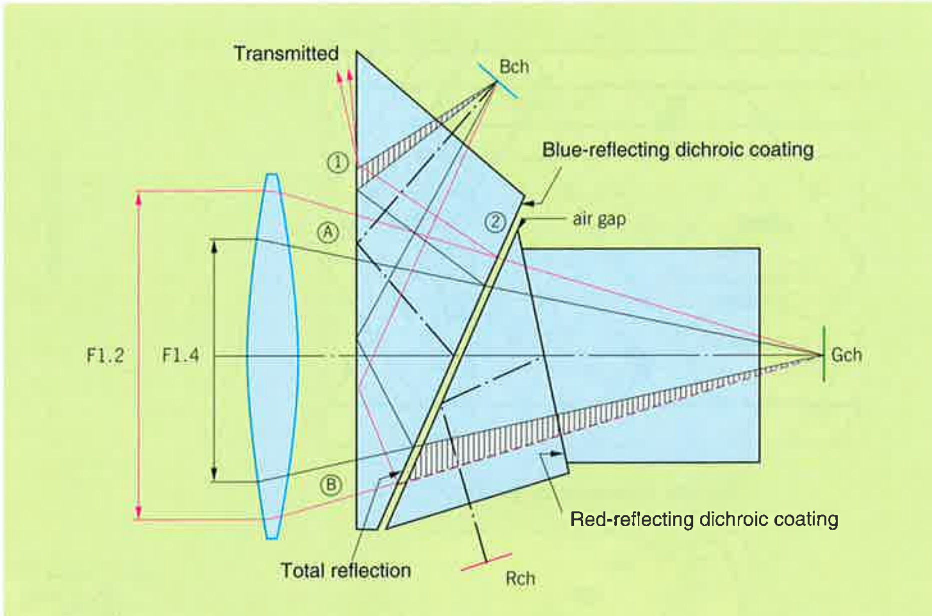


Fig.109 F1.2 lens fitted to a three-piece F1.4 prism

7.6 Color Separation Prism for a CCD Camera

1. Characteristics of color separation prisms for a CCD camera

Color separation prisms used in a CCD camera have three main characteristics in terms of the way imaging devices are fixed and the property of the device.

(1) Stability in holding CCDs

In a pick-up tube camera, the pick-up tubes were held on an alignment housing which contained the prisms. On the other hand, CCDs are fixed directly to the color separation prisms in a CCD camera. For this reason, the color separation prisms for a CCD camera are required to have the characteristics mentioned below.

- The mechanical strength of the adhesive layer has to be sufficient to keep the CCDs steady when vibration or a shock is applied.
- The prism base and prism glass have to have the same coefficient of linear expansion to prevent registration errors when the temperature changes.

To solve the problems mentioned above, the material used for the prism base and the adhesive were carefully selected. For the adhesive, in particular, experiments were repeatedly carried out to check the temperature dependence and the adhesive strength. The way it is used and so further were reconsidered in detail to enable optimum use under any circumstances. It is also necessary to improve the manufacturing precision of the prism components themselves.

(2) Spectral characteristics

CCDs have a high level of spectral sensitivity nearing the near infrared region such that they require some means to prevent near infrared light leakage.

To solve these problems, the use of the cyan filters shown in Fig. 110 as chain lines is effective. Cyan filters inhibit near infrared regions significantly, such that a CCD camera fitted with a cyan filter will produce a very close approach to the spectral sensitivity characteristics of the pick-up tube camera used previously, as marked by a chain line in the figure. Optimal prism spectral characteristics have been laid out to allow for this.

(3) Countermeasures against ghosting

Unlike pick-up tubes, CCDs are free from burning. For this reason, ghosting and flaring which occur when a light spot is in the image area cause problems in a CCD camera, which has never been thought of in the conventional pick-up tube cameras. This may be attributable to the metallically lustered acceptance surface of the CCD, microlenses installed for better sensitivity and pixels arranged in regular order, causing reflections that accompany diffraction. Therefore, stronger countermeasures are taken against ghosting caused by high-intensity light passing through the color separation prisms as well as through the lens on a CCD camera.

2. Precise fixation of CCDs

In a CCD camera, tracking cannot be adjusted mechanically and registration cannot be adjusted electrically. They are determined by the precision of CCD fixation. Therefore the positioning of CCDs with high accuracy is required.

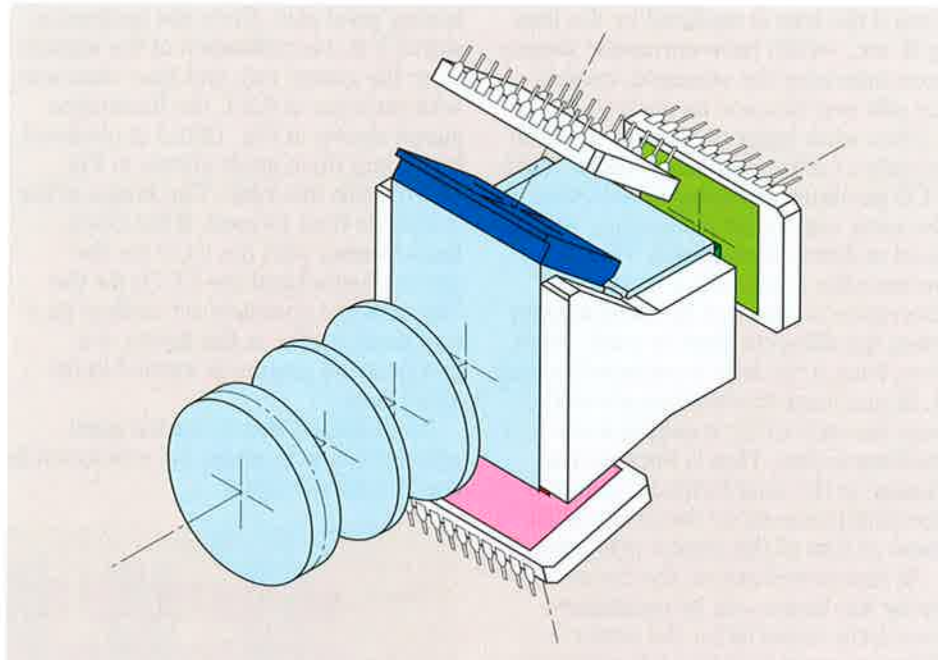
There is a standard for the positions of three CCDs along the optical axis (tracking positions) which ensure compatibility (see Figs. 73 and 74). A master projector whose longitudinal chromatic aberration is designed in accordance with the standard is used to adjust the CCDs to the standard positions.

3. Compatibility of prisms made of different materials

In practice, non-standard glass is often used for cameras because of the special designing requirements or to reduce the cost.

Since the longitudinal chromatic aberration changes with the Abbe number of the prisms, there would appear to be a danger that the tracking of the lens will shift. However, the compatibility is maintained as follows:

In Fig.111, X is a prism whose material conforms to the standard, and the CCDs can be fixed at the standard positions using a master projector.



Color separation prism for a CCD camera

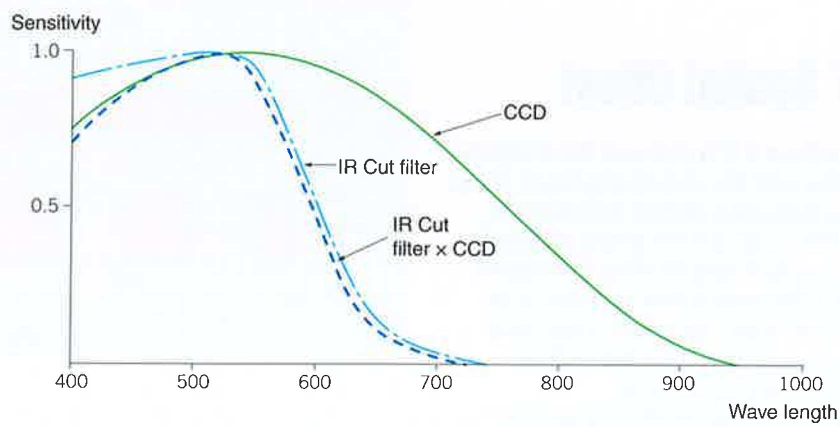


Fig.110 Spectral sensitivity differences between a CCD and pick-up tubes

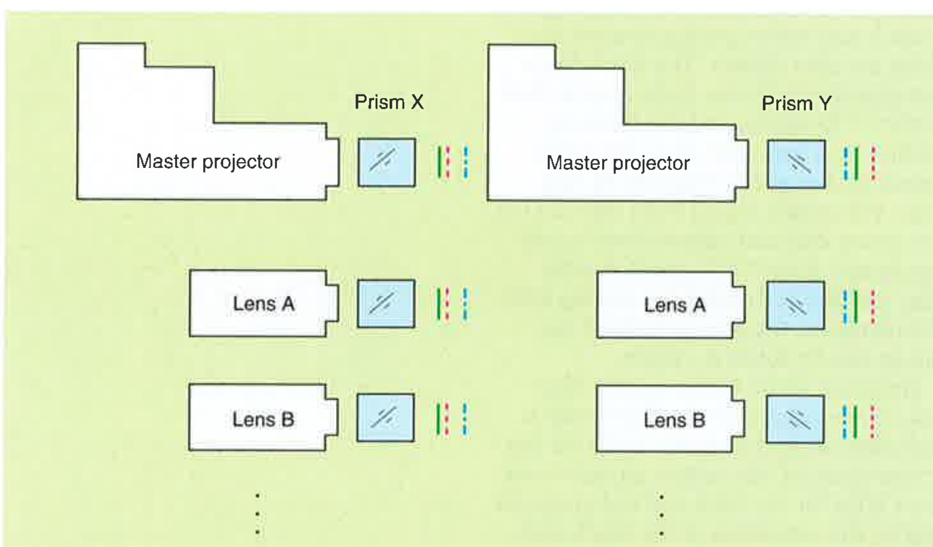


Fig.111 Compatibility of prisms with different materials

Even if the lens is replaced by the lens A, B, etc., which have chromatic aberrations matching the standard, images are still best focused on each CCD.

Then what happens if prism Y which is made of different glass is used? If the CCD positions are determined using the same master projector, they will be fixed at different positions. That is because the longitudinal chromatic aberration is changed by fixed amount when the different glass is used. However, even if the lens is replaced by lens A, B, etc., best focused images still form on each CCD, resulting in no tracking errors. That is because the change in the longitudinal chromatic aberration caused by the prism is the same as that of the master projector.

As mentioned above, the compatibility for the lenses can be maintained even if the material for the prism is different, provided the CCD positions are determined using a master projector.

7.7 Spatial Offset

In a three-CCD camera, the CCDs for the blue and the red channels are fixed with a half pixel shifted horizontally from the CCD for the green channel. This is called spatial offset (half-pixel offset). The resolution appears to be improved when the pixel offset technique is used. Its principle will be explained using a figure.

Fig. 112(a) shows the horizontal arrangement of the CCDs for the blue and the red channels, and the images of a black and white grating formed on them are also shown. The black lines are repeated with the cycle double that of the CCD pixels, and the lines are shifted by a half pixel from the CCD pixels for the green channel. In this case, the output signal from the CCD of the green channel cannot form a grating image. If the CCD pixels for the blue and the red channels overlap with the pixels for the green channel, no image can be formed, either.

However, if the CCDs for the blue and the red channels are fixed with a half pixel shifted from the CCD for the green channel, the output signals from the CCDs for the blue and red channels will be the repetition of the black and white colors coming from each neighboring pixel pair. Since the luminance signal Y is a combination of the signals from the green, red, and blue channels with the ratio of 6:3:1, the luminance signal shown in Fig. 112(c) is obtained by adding the signals shown in Fig. 112(b) with this ratio. The image of the grating is then formed. If the black lines overlap with the CCD for the green channel and the CCDs for the blue and red channels are shifted by a half pixel, unlike in the figure, the image of the grating is formed in the same way.

As explained above, spatial pixel offset helps to improve the resolution in the luminance signal.

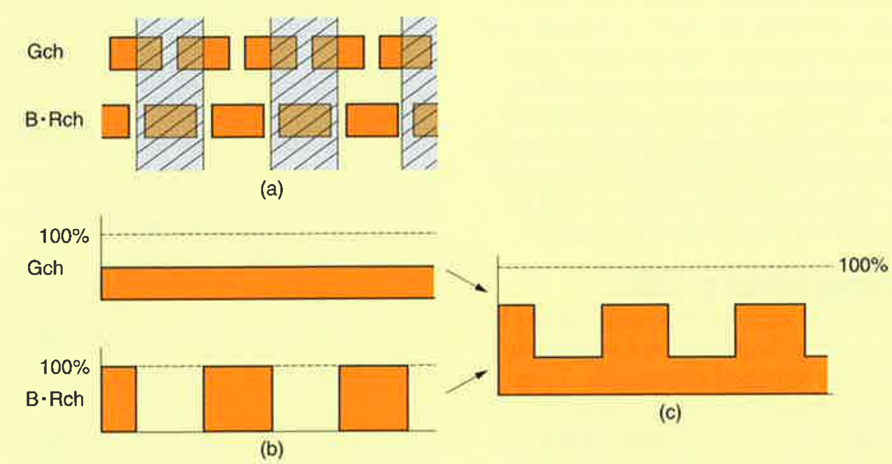


Fig.112 Spatial offset

INDEX AND GLOSSARY

Terms not discussed in the text are defined briefly below.

A

Abbe number

A quantity expressing the dispersion of optical glass. Let n_F, n_d, and n_C be the refractive indices at the F spectral line (486.1 nm), d line (587.6 nm) and C line (656.3 nm). The Abbe number ν_d is then:

$$\nu_d = \frac{n_d - 1}{n_F - n_C}$$

Aberration ········ 31

Aberration free lens ········ 39

Aberration theory ········ 32

Achromat

A lens whose chromatic aberration is corrected by combining two or more lens elements.

AF (Auto focus) ········ 16

Afocal system ········ 48

Angle of view ········ 12,19

Anti-reflection coating ········ 34

Anti-reflection grooves ········ 37

Aperture efficiency ········ 26

Aperture ratio ········ 21

Apochromat

A lens whose chromatic aberration is corrected for three different wave-lengths.

Aspect ratio ········ 18

Aspherical Lens ········ 32

An aspherical lens is a lens having its lens surface formed into an arbitrarily ideal, not spherical, shape for aberration correction purposes. Aspherical lenses are produced in one of two ways: polishing and molding.

Astigmatism ········ 31

B

Back focal length ········ 24

Beam splitting prism ········ 58,64

Same as color separation prism

Black body ········ 55

Same as double refraction

Burning ········ 36

A phenomenon in which an image remains even after the light is cut off, occurring when bright light enters a pick-up tube.

C

CAD ········ 37

Computer aided design

CAFS (Constant Angle Focus System) ········ 8

The Canon-proprietary name of a technology of canceling the changes in the angle of view caused by the movement of the lens unit in the front lens group in a focusing operation by shifting the scaling unit in a direction of counteraction.

Cam ········ 6

CCD (Charge coupled device) ········ 36

CCDs are made up of minute optical sensors arranged on the surface of silicon crystals. The charges stored in the sensors are read-out by transferring them to neighboring sensors one after another. They are categorized into FT (frame transfer), IT (interline transfer) and FIT (frame interline transfer) types, according to the method of charge transferral.

CC filter (Color Conversion filter) ········ 55

Change of focus ········ 6

Movement of the image plane due to zooming.

Chart ········ 42,44

(1) A black and white chart used to measure the resolving power of a lens.

(B) A test pattern used to adjust a camera.

Chromatic aberration ········ 28

Circular polarized light ········ 61

Close-up ········ 52

Close-up lens ········ 52

Coating ········ 34

Color conversion filter ········ 55

Color separation prism ········ 58,64

Color temperature ········ 55

Comatic aberration ········ 31

Compensator ········ 6

Contrast ········ 27

Cos^4 law ········ 26

Critical angle

The minimum angle of incidence at which total reflection occurs, when light is incident from a medium of higher refractive index onto a medium of low refractive index.

Cross filter ········ 57

Curvature of field ········ 31

Mattebox 9

An apparatus installed on the front of a lens that enables various optical filters to be inserted for special effects as well as acting to shade the lens from the sun. Matte boxes are often used for cine photography.

Meridional 31

Minimum Object Distance (MOD) 23

Mired 55

Modulation Transfer Function (MTF) 26

Moire 61

A pattern produced by overlaying one regular pattern on another.

Mount 24

N

ND (Neutral density) filter 54

Near infrared

The wavelength band from 700 nm to 1300 nm.

Numerical aperture

A quantity expressing the brightness of an optical system. Let α be the angle subtended with respect to the entrance pupil by an object point in a medium of refractive index n. The numerical aperture (NA) is then n sin α. The brightness of microscope objective lenses is often expressed in terms of NA. The relationship with the F-number is:

F-number = 1/(2·NA)

O

Object dimensions 19

Optic axis 62

A direction along which the refractive index is constant in an optical crystal.

Optical axis

The line on which the centers of curvature of the surfaces in an optical system lie.

Optical glass

A homogeneous glass with specific optical properties.

Optical transfer function (OTF)

Same as MTF. See Section 2.11.

Optical Vibration-proof System 11

A process of canceling blurs in imaging caused by camera shaking and other conditions by varying the optical axis in an optical means. Processes that have reached the stage of practical usefulness include lens shifting and variable apex-angle prism.

Ordinary ray 62

A ray whose velocity does not depend on the direction that it propagates after being split into two when entering a double refraction crystal.

P

Parallax 16

Parallel polarized light 56,60

Paraxial theory 32

Permissible circle of confusion 14

Perpendicularly polarized light 56,60

Plane polarized light 56,61

Polarizer 56

Polarization 56,61

Principal ray 25

Pupil

A general term for entrance pupil or exit pupil.

Q

Quartz plate 61

R

Range calculator 20

Reflection

A phenomenon in which light incident on a boundary between media returns into the medium on the incident side.

Refraction

The bending of light rays incident on a medium at the surface of a medium.

Refractive index 24

The ratio of the speed of light in a vacuum to the speed of light in a medium.

Registration 29,43

Relay group 6

Residual chromatic aberration 28

The slight aberration that remains after the main aberration have been corrected.

Resolving power 26

Retrofocus type ··· 7

S

Sagittal ··· 31

S-component ··· 56,60

Secondary image resistration phase-detection system ··· 16

Secondary imaging lens ··· 16

Secondary spectrum ··· 28

Seidel's five aberrrations ··· 31

Siemens star ··· 42

Single lens ··· 18

A lens with a single components, or a lens with a fixed focal length (as opposed to a zoom lens).

Skylight filter ··· 54

Smear

A phenomenon in which blurring is caused by high-intensity light entering the surface of sensors on a imaging device. In a CCD, peculiar smears in which vertical lies appear above and below a high luminance object sometimes occur. However, recently these smears have become uncommon due to improvements in CCDs.

Snell's law ··· 32

Soft focus filter ··· 57

Spatial frequency ··· 26

Spatial offset ··· 66

Spherical aberration ··· 31

Spurious resolution

A phenomenon in which black and white stripes finer than the resolution limit appear to be resolved, but with black and white reversed. Occurs when the MTF is negative.

Spurious signal ··· 61

Same as aliasing.

Sputtering ··· 34

T

Tangential

In the tangential direction. Same as meridional.

Tarnish

A thin, altered layer on the surface of optical glass, caused by the action of moisture, acid, etc. One effect of a coating is to prevent tarnish.

Telecentric ··· 25

Telephoto type ··· 7

Tele-side converter ··· 50

T number ··· 22

Total reflection ··· 58

When light passes from a medium of higher refractive index to a medium of lower refractive index, if the angle of incidence is greater than a certain critical angle, all of the light is reflected at the boundary between the media.

Tracking ··· 42

Trimming filter ··· 58

TTL (Through The Lens) ··· 16

U

UCS (Uniform chromaticity scale) ··· 62

Ultraviolet ··· 54

The wavelength band from 300 nm to 400 nm.

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TV OPTICS III

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The Specification and data regarding the products described herein are subject to change without notice.

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