Measurement and analysis of the performance of film and television camera lenses

Tech. 3249–E September 1995

CONTENTS

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Preface

The technical quality of a transmitted television picture depends on several factors, one of the most important of which is the quality of the camera lens. A complete objective assessment of the optical and mechanical performance of a lens demands the measurement and evaluation of a large number of different parameters. In general, this is a rather difficult and time–consuming task. However, the number of parameters to be measured can be reduced, to some extent, depending on the intended application of a lens and on the kind of test.

Chapter 1 of the present document sets out the context within which any specialized measurements on camera lenses are made. Lenses used in broadcasting, whether for film or electronic programme–making, are complex opto–mechanical devices which demand the highest standards of craftsmanship and require specially–adapted forms of measurement and testing. Such is the degree of specialization required, in terms of both measurement systems and the skills of the test engineer, that careful consideration needs to be given to the necessity, feasibility, and economics of making particular types of tests.

Chapter 2 gives a selection of optical parameters which can be measured during the objective assessment of lenses, with descriptions and formal definitions of the characteristics and details of the conditions under which they should be measured. These methods cover either zoom lenses or fixed focal–length lenses, and the differing requirements of large zoom lenses for electronic studio or outside broadcast cameras, of lightweight lenses for electronic news–gathering, and of lenses for 16–mm and 35–mm film cameras are taken into account. The basis of the document is the demands made on lenses for conventional 625–line television in the 4:3 aspect ratio. Nevertheless, to the extent possible in the present state of development of wide–screen and high–definition television technologies, the characteristics of lenses for 16:9 aspect–ratio television, electronic HDTV and Super 16–mm film production for television have been covered also.

For each characteristic the chapter also gives a series of typical values and offers guidance on the interpretation of measurement results. This interpretation is based on long experience in the evaluation of picture quality. In this respect, it should be recalled that the relationship between the objective measurements on a lens and the subjective quality of the displayed picture is an extremely complex one, involving amongst others, various psychological and physiological parameters that cannot be measured. For some of the characteristics, if the indicated tolerances are not respected then the picture quality may be seriously degraded, even if all the other tolerances are respected.

Chapter 3 gives similar descriptions for several mechanical characteristics. In effect, the optical performance of a lens is critically dependent on its mechanical design and on any deterioration of the mechanical system caused through wear or accidental damage. It is not possible to cover all aspects of mechanical design and performance owing to the extreme diversity of mechanical configurations found in modern lenses. The Chapter does nonetheless set out a general design and manufacturing philosophy serving as a guide in the general assessment of lens performance, notably in the context of type testing.

Chapter 4 considers the adaptation of the evaluation of the characteristics of lenses according to their intended applications. The permutations of lens types (multi–purpose lenses for studio and outside–broadcast use, lightweight lenses for electronic news–gathering (ENG) and electronic field production (EFP), types of camera (television cameras with pick–up tubes or CCD sensors, or film cameras of various formats) and programme–making environments (studio, outside–broadcast, news–gathering, etc.) are numerous, and the relative importance of specific lens characteristics may be different in each case.

The *Appendix* considers the scope for simplification in the presentation of the mass of data resulting from a full series of tests and measurements on any given lens, as a means of facilitating the selection of a lens for a given application, or comparisons between lenses.

To relieve the reader of the inconvenience of switching from one part of the document to another by means of cross–references, the text has been arranged so that lenses for film and television camera lenses can be dealt with at the same time. In this simultaneous description, all information which is identical for both kinds of lens extends across the full page width, while the page is divided into two columns wherever there are differences. This arrangement has the added advantage of highlighting the differences, and the reasons for them, between the measurement techniques for film and television cameras lenses. Where there are significant differences relating to lenses within either of these broad categories (e.g. between lenses for CCD or tube cameras, or between conventional and high–definition systems) these differences are also highlighted. In the absence of any distinction of this kind, the information given is relevant to all lenses in all applications.

Note concerning measurement equipment

Many of the measurement methods described in this document require the use of sophisticated optical instruments. Where possible, indications have been given of potential suppliers of apparatus which will give satisfactory results. However, the mention of specific manufacturers, or specific products, does not imply that other sources of suitable equipment do not exist, and does not imply any preference on the part of the European Broadcasting Union in favour of any particular products and manufacturers.

As an alternative to the listed measuring instruments, the necessary modules for the measurement of modulation transfer function (MTF) and the other parameters can also be purchased individually from the well–known suppliers of precision optical equipment, and assembled to form a custom–built test bench. The accuracy of the results will be dependent on the precision and stability of the modules used.

Chapter 1

Introduction to lens measurement techniques

1.1. Choice of measurement methods

In general, three different kinds of tests are made on lenses by the broadcasting organizations:

- *Type test:* This is a full–scale test, carried out when a new type of lens is produced. There is sufficient time available to permit detailed measurements to be taken of all important characteristics.
- *Acceptance test:* This test is carried out when the type test was satisfactory and several specimens of the same lens type are purchased and have to be accepted into operational service. Not all of the type–test measurements need to be repeated; normally only spot checks of the most important parameters are carried out, to ensure consistency.
- *Routine checks:* This test is carried out either periodically, to detect any significant deterioration in good time, or because of complaints. Only a restricted number of measurements, of selected parameters, is carried out.

From enquiries among the EBU Member organizations, it appears that the number of measurements actually taken in these three categories differs from one broadcaster to another. Accordingly, the present document specifies measurement methods for all the technical parameters which may be of interest, and included in a complete type test, when assessing the performance of a film or television camera lens. For acceptance tests and routine checks, it is recommended that an appropriate selection of these parameters is chosen.

1.2. Accuracy and reproducibility of measurement results

The results of optical and mechanical tests are critically dependent on the test methods and conditions employed. In order to permit valid comparisons between results obtained using different lens–testing instruments, uniform measuring conditions have to be specified which take into account all the factors which may influence the measurements. To be meaningful, the performance of a lens must be determined under conditions which duplicate, as far as possible, the conditions under which the lens is likely to be used. As a consequence, distinct measurement conditions must be defined for certain parameters, applying specifically to lenses for film cameras, and for television cameras.

For each of the parameters specified in this document, appropriate measuring equipment is described. The equipment referred to is now available (although some minor adaptation may be required for the present purposes) for the measurement of the optical performance of lenses under these standard test conditions.

The accurate measurement of the optical performance of lenses requires the use of very sophisticated – and therefore expensive – equipment. However, for comparative measurements in practical broadcasting operational areas (for example, for routine checks) where relative rather than absolute values are normally sufficient, simpler approaches can be adopted. For television camera lenses, test procedures for certain optical parameters (resolution, geometry, flare, white shading, etc.) are described in [1] and [2]. In these tests, the camera is included in the test chain, so the results relate to the overall performance of the lens, the beam splitter and the camera tubes or CCD sensor. This is in contrast to the tests described in the present document, in which the lens is tested in isolation.

1.3. Presentation and interpretation of measurement results

The interpretation of the results of measurements of the various lens characteristics discussed in this documents requires a long and rather extensive experience in the assessment of picture quality.

In the description of the measurement methods, some support is given to the user, in the form of indications of typical values which can be expected in lenses designed for the zoom ranges normally found in television operations. These values refer to measurements on the basic lens, without range extenders.

In some cases it might be preferable to present the measured results in the form of bar–charts. This form of visual presentation of the large amount of numbers collected during tests on lenses can considerably simplify the evaluation and very quickly give an overall impression of the lens performance, enabling a larger number of users easy access to the large quantity of information hidden in the raw test data.

Appendix 1 to the present document gives an example of the use of bar–charts for the presentation of lens measurement results.

1.4. Performance targets

After measurements have been taken, they will generally be compared to an appropriate reference, which will depend on the type of test being performed (see *Section 1.1.*). This reference may be a target specification contained in an invitation to tender for the supply of lenses (the case of type testing), or the results of the type test (reference for an acceptance test). Once a lens has been taken into operational use, the reference may be the results of the previous routine test, considered in conjunction with the type test results or the manufacturer’s specifications, or even a simple comparison with the personal experience and knowledge of the person carrying out the tests.

The definition of a full set of lens specifications covering all broadcast applications and all the characteristics defined in *Chapters 2* and *3*, is beyond the scope of the present document. Indeed, it is unlikely that any such specifications would satisfy all broadcasters. Except where specifically stated otherwise, the values indicated in the present Chapter are *typical* of the values encountered in lenses currently used by broadcasters.

In general, the EBU specifications for camera lenses are based on relevant broadcasting specifications that have proven to be useful in operational practice in the past and, wherever possible, they have been kept within the existing ISO Standards.

1.5. Influence of picture aspect ratio and image resolution

The measurement methods and performance targets referred to in this document are based essentially on the requirements of conventional 625–line colour television production in the 4:3 aspect ratio. While in many cases the requirements for lenses adapted to other systems are the same, it is important to be aware of some differences in the case of wide–screen and high–definition camera systems.

1.5.1. 16:9 aspect ratio

In 625–line television systems with an aspect ratio of 16:9, the image diagonal is the same as in the 4:3 format. Consequently some of the measurement conditions and performance targets will be the same. However, cameras are also available which can be switched to operate with either 4:3 or 16:9 aspect ratio. Lenses are also available which take this feature into account by using image size converters placed in the range extender turret. In switchable systems the length of the image diagonal may change as the aspect ratio is changed, and this must be kept in mind when measurements are taken and interpreted.

1.5.2. HDTV

The requirements of lenses for electronic HDTV television cameras differ from those for conventional systems mainly in respect of the modulation transfer function and chromatic aberrations.

1.5.3. Film image formats

In the case of film camera lenses, the cut–off frequencies given in this document are based on the scanned area for the film format in question, as defined in [3].

1.5.4. Super 16–mm film

All measurement conditions and other recommendations for lenses used with 16:9 aspect ratio television cameras also apply to lenses for the Super 16–mm film format, except the cut–off frequencies.

1.6. General technical considerations

Before measurements are taken, the test conditions must be set to the prescribed values, with sufficient precision. Care must be taken to take account of any factors which may influence the accuracy of measurements. In particular, the environmental conditions such as temperature and humidity must be kept sufficiently constant and other external disturbances such as mechanical vibrations, air turbulence and stray light must be avoided. All measurements should be made with the greatest possible precision. For periodic checks of the calibration of the measuring instruments, it is essential to use calibrated test lenses.

Television camera lenses are generally used with a prism splitter block between the lens and the camera tubes. When carrying out measurements of image quality on television lenses, a glass block must be inserted in the optical path. This block must have the equivalent length of the splitter block (tolerance ± 0.5 mm) and equivalent optical properties (dispersive power), and must also simulate any filters normally present in the camera and the glass comprising the front face of the green pick–up tube. The relevant data should be obtained from the camera manufacturer. This glass block should be removed from the optical path during all photometric measurements.

CCD cameras have a pre–defined axial (focal plane) offset of the red and blue sensors with respect to the green sensor. These are different for different CCD sensor sizes, and for cameras with conventional or high–definition imaging systems. The specifications are given in EBU Technical Information I 21 [4]. When measuring the modulation transfer function (MTF) and chromatic aberrations of lenses for such cameras, the offsets must be taken into account.

Most modern zoom lenses have built–in range extenders. These cause some reduction in the performance of the lens and this should be evaluated in relation to the effect of a change of relative aperture. It should also be quantified in relation to the operational requirements.

Each individual element in a lens has its own optical axis which, when the parts are assembled, should give a common optical axis for the complete lens; this in turn should ideally align with the mechanical axis of the mount. In practice this is not always the case, and the effect will be that measurements taken off–axis will not be symmetrical and will modify those taken on–axis.

To ensure that results can be reliably compared, the optical axes of the lens and the test bench should be coincident. (It should be noted in this respect that mechanical misalignment of the camera/lens interface may cause problems.) The regular verification of any type of measuring system with a calibrated lens is essential.

Chapter 2

Optical characteristics

This Chapter describes detailed measurement procedures for the following optical characteristics of film and television camera lenses:

- Modulation transfer function and astigmatism
- Flange focal distance / Back focal distance
- Zoom tracking errors – axial
- Zoom tracking errors – lateral
- Chromatic aberrations – lateral
- Chromatic aberrations – longitudinal
- Spectral transmittance
- Transmission factor and aperture scales
- Relative field illuminance (white shading)
- Veiling glare (flare)
- Picture height distortion

Each description begins with a definition or explanation of the characteristic. This is followed by details of the special conditions which must be provided to ensure that the results are accurate and comparable with results taken by other organizations or lens manufacturers. The comparability of results is enhanced by the adoption of a common form of presentation of the results, and indications are given in this respect. To assist in the interpretation of the results of measurement, indications are given of typical parameter values for lenses conforming to typical requirements of broadcasters. In some cases, specifications are given. Finally, information concerning the equipment needed to carry out each test is given.

Except where indicated otherwise, the parts of the text concerned with television camera lenses are applicable to all types of television cameras regardless of whether they use conventional pick–up tubes or charge–coupled device (CCD) sensors. However, due to the absence of error compensation in present–day CCD cameras, it is necessary that these lenses are made to tighter tolerances. This applies in particular to chromatic aberrations. When making measurements on CCD camera lenses it is necessary to take into account the offsets of the red and blue focal planes specified by the manufacturer.

The order of presentation of the measurement procedures in this document does not imply any order of importance of the corresponding characteristics in determining the overall suitability of a lens for any particular application.

2.1. Modulation transfer function (MTF) and astigmatism

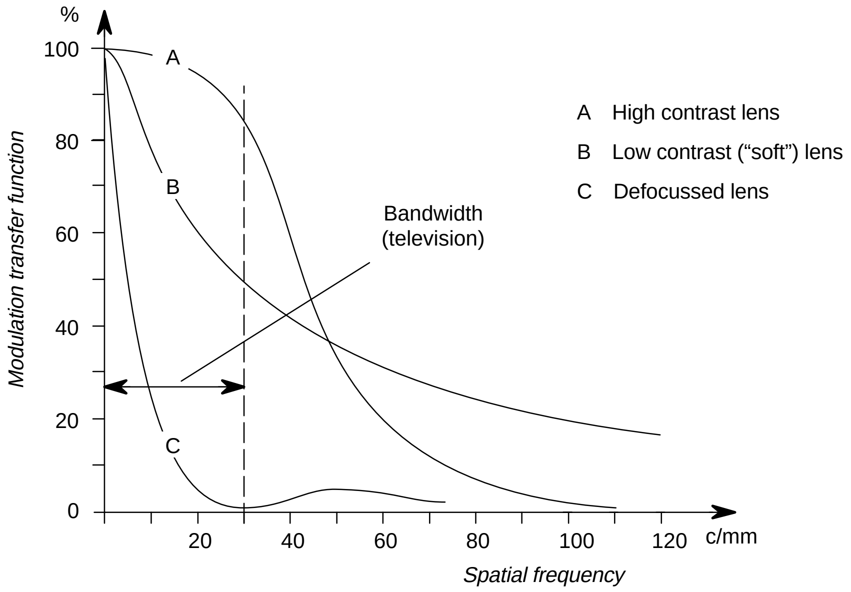
As mentioned in the introduction, this document establishes a set of objective criteria which will help to describe lens properties affecting picture quality. One very important aspect in determining overall picture quality is picture sharpness. However many factors determine the impression of sharpness or resolution of detail in a picture.

The most important single parameter determining picture sharpness is the modulation transfer function (MTF). This quantity can be measured objectively and will reveal a large number of deficiencies and defects in a lens or a lens system. MTF may be thought of as being analogous to the frequency response of an electronic amplifier. It must be appreciated that there is a difference in the use of the term “frequency”. In electronics, frequency is a temporal quantity, a function of time, whereas in the case of MTF the frequency is a function of length; accordingly, it is referred to as a “spatial frequency”.

It is important to measure the MTF of a lens because it gives an indication of the manufacturing quality of the lens, including the mechanical mounting of the constituent parts and the operating system (focussing, zoom, iris) and the positioning of the individual optical elements in the system. It is also likely to highlight any degradation in performance caused by wear during normal operation long before it can be detected as reduced picture quality. The MTF isolates the lens from the complex lens/camera/reproduction system and is therefore a valuable means of assessing new lenses, as well as serving for acceptance tests and routine checks.

The shape of the MTF curves gives an indication of the combined effects of aberrations, design and manufacturing tolerances, and wear through normal use if the original MTF curves are available for comparison.

Lenses can be classified according to the shape of the MTF curve, as shown in *Fig. 1*. The curves shows whether the lens is of a “high contrast” type, or “soft”. High–contrast lenses (curve A in *Fig. 1*) may be preferred for television, whilst low–contrast lenses (curve B) are more suited to films intended for optical projection.



Note: The spatial frequency scale corresponds to the use of 2/3–inch tubes for a television camera, or 16–mm film.

Fig. 1 – Classification of lenses according to the shape of their MTF curves (from [5]).

It is important that the off–axis MTF values, obtained at a given focal length on either side of the optical axis, should match to within 10%. A large difference between the radial (*R*) and tangential (*T*) MTF curves is an indication of astigmatism; this is one of the five forms of monochromatic aberration which is present in every lens.

2.1.1. Definition

The *modulation transfer factor* is the ratio of the image modulation to the object modulation at a particular frequency, for a sine–wave target or grating.

The *modulation transfer function* (MTF) is the variation of the modulation transfer factor with spatial frequency. This function is normalized to unity at zero spatial frequency.

Note: A mathematically rigorous definition of the modulation transfer function is given in [6]; MTF is defined there as the modulus of the Fourier transform of the line–spread function of the imaging system.

2.1.2. Measurement conditions

a) *Focus adjustment*

The modulation transfer function is directly dependent on the focussing procedure. The following guidelines are therefore given for the optimization of the focus adjustment.

Film camera lenses	Television camera lenses
No glass block.	The glass block simulating the prism splitter block, tube face, filters etc. must be inserted in the optical path (green channel).
The flange focal distance of the lens under test should be set accurately to the design dimension given by the manufacturer. The focussing assembly is then adjusted at maximum focal length (in the case of a zoom lens). The aim is to ensure that the flange focal distance is the same at both ends.	The back focus should be adjusted at minimum focal length and the front focus (or lens focus) is set at maximum focal length, by tracking up and down. The aim is to make the back focal distance the same at both ends.

These adjustments should be carried out to obtain the best response of the modulation transfer factor under the following conditions:

– at the cut–off frequency (this depends on the film gauge (*Table 1*) or the pick–up tube/sensor diameter (*Table 2*, *Table 3*));

– on axis;

– when focussed to infinity, or at least 15 times the maximum focal length (if this is not the case, the distance should be recorded with the results);

– at full aperture.

In practice, this focussing condition may be implemented by assuming that the optimum image plane is mid–way between the two planes at which the MTF has fallen to 50% of the maximum value of MTF.

Once adjusted in this way, the optimum image plane must not be altered during the measurement procedure. Any deviations from this focus adjustment (e.g. use of a back focus setting recommended by the manufacturer) must be indicated with the measurement results.

Table 1 – Cut–off frequencies and nominal apertures for different film gauges.

Film width (mm)	**Image diagonal** (mm)	**Cut–off frequency** (c/mm)	**Nominal aperture** (f–stop)
16	12.5	30	2.8
Super 16–mm			
(16:9/625–line)	13.60	23	
HDTV	13.60	81	
35	27.2	15	4

Table 2 – Cut–off frequencies and nominal apertures for different television camera tube sizes (television systems of conventional definition)**.**

Tube diameter (inches)	(mm)	**Image diagonal** (mm)	**Cut–off frequency** (c/mm) (*Notes 1, 2*)	**Nominal aperture** (f–stop) (*Note 3*)
1 1/4	30	21.4	15	4
1	25	16	20	3.5
2/3	18	11	30	2.8
1/2	13	8	40	2

Notes

1 These values are for 4:3 aspect ratio and for 16:9 systems having the same image diagonal. If the image diagonal changes in a 4:3/16:9 switchable system, the cut–off frequency will change in proportion.

2 These values are a compromise covering television systems with bandwidths of 5 and 5.5 MHz.

3 If tubes of different sizes are used in the different channels of a camera, the choice of nominal aperture is determined by the format of the green tube.

Table 3 – Cut–off frequencies and nominal apertures for different television sensor sizes (high–definition television systems)**.**

Sensor diameter (inches)	(mm)	**Image diagonal** (mm)	**Cut–off frequency** (c/mm) (*Note 1*)	**Nominal aperture** (f–stop)
1	25	16	69	3.5
2/3	18	11	100	2.8
1/2	13	8	138	2

Note

1 The spatial cut–off frequency is based on systems with 1920 samples per active line.

It should be noted that the image plane defined above does not take into account the depth of focus corresponding from the dimension of the “least circle of confusion” which, in the case of lenses for television, is determined by the width of the scanning line in the television raster. For some image points, and in particular for points which are off–axis, better MTF values might be found if the focus is adjusted, within the range of the depth of focus. In a lens which exhibits astigmatism, the best focal plane would be that in which the *R* and *T* MTFs have the same value. To limit the amount of measurement data, and to simplify the evaluation of the results, these considerations are not taken into account in this document.

b) Measurement frequencies

The modulation transfer factor should be measured at at least two spatial frequencies, equal to 2/3 and 3/3 times the system cut–off frequency (see *Table 1, Table 2* and *Table 3*).

c) Apertures

Measurements should be taken at full aperture and at the nominal apertures shown in *Table 1, Table 2* and *Table 3.*

d) Conjugate

Measurements should be taken at the infinite object conjugate, or at at least 15 times the maximum focal length. If a shorter distance is used, the distance should be recorded with the results.

e) Focal lengths

In the case of a zoom lens, the following focal lengths should be used:

- minimum;
- maximum;
- intermediate positions obtained by doubling the minimum focal length until the maximum is reached.

If range extenders or other lens attachments are fitted, the tests should be repeated under extreme conditions (it may be necessary to re–adjust the front focus.)

f) Spectral conditions

The modulation transfer factor is very dependent on the spectral conditions. It is therefore necessary to define the spectral distribution of the test pattern radiation and the spectral sensitivity of the image analyzer, bearing in mind the intended application of the lens under test.

The illuminant should have a correlated colour temperature of 3100 ± 100 K.

Film camera lenses

The spectral sensitivity of the analyzer should be adapted to the CIE visual luminosity function Vλ (photopic eye response, see *Fig. 2*).

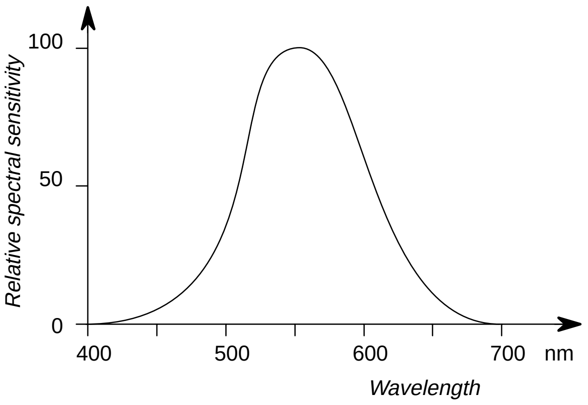


Fig. 2 – Photopic eye response Vλ .

Television camera lenses

In the case of cameras of conventional definition, the spectral sensitivity of the analyzer should be adapted to the green channel response (positive lobe) of a television camera having the EBU primaries (see *Fig. 3*).

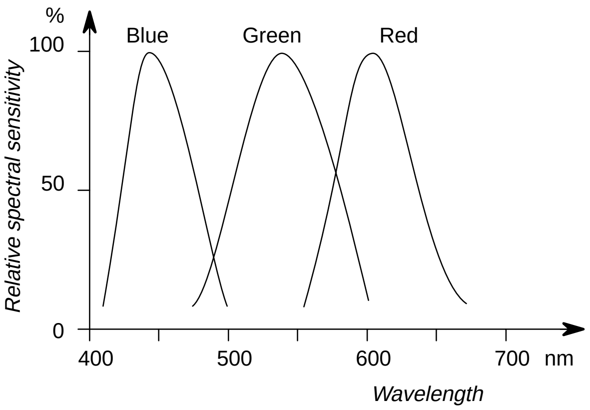


Fig. 3 – Colour matching functions (positive lobes) of a television camera conforming to the EBU primaries.

A combination of practical filters which will approximate to the spectral sensitivity of a detector with type S20 photocathode to the V_λ response is given in *Table 4*.

Table 4 – Practical filters which will approximate the spectral sensitivity of a detector with type S 20 photocathode to the film sensitivities and photopic eye response V_λ .

R	G	B
Kodak Wratten filter No. 9 plus sharp infra–red cut–off filter at 670 nm.	Kodak Wratten filter No. 99.	Kodak Wratten filter No. 98.
V_λ		
Kodak Wratten filter No. 102 Schott KG3, 3 mm Schott FG15, 2 mm		

This integral weighting function takes into consideration the relative importance of spectral MTF contributions to visual sharpness. In other words, it establishes a correlation with the way the sharpness of the reproduced film picture is perceived by the observer.

In most modern television cameras it is common practice to derive those picture details which are decisive for the sharpness from the green channel, although these details may also be derived from the blue or red channels as well, under certain conditions (e.g. special lighting effects). As a compromise for the measurement of the modulation transfer factor in the individual colour channels, it is therefore recommended to measure it in the green channel only.

If necessary, measurements may be made also in the blue and red channels using the appropriate filters listed in *Table 5*.

Table 5 – Practical filters which will approximate the spectral sensitivity of a detector with type S 20 photocathode to the camera colour matching functions.

R	G	B
Corning 2–73 (1.5 mm) *plus* Corning 4–97 (3 mm).	Schott VG9 (1.5 mm) *plus* Schott GG495 (3 mm).	Corning 3–74 (3 mm) *plus* Corning 5–59 (4 mm).

In the case of HDTV camera systems, the filter characteristics shown in *Table 6* should be used (these characteristics are taken from a specification for the camera/lens interface of 1–inch HDTV CCD cameras, agreed in principle within the EBU).

Table 6 – Filters providing the correct spectral conditions for measurements on lenses fitted to HDTV cameras having 1–inch CCD sensors.

R	G	B
Hoya O–58 (1.0mm) *plus* short wavelength dichroic coating (λ/2=580 nm) *plus* long wavelength cut–off dichroic coating (λ/2=665 nm)	Hoya Y–50 (1.0 mm) *plus* Hoya G533 (0.8 mm) *plus* long wavelength cut–off dichroic coating (λ/2=580 nm)	Hoya L–42 (1.5 mm) *plus* Hoya B440 (2.0 mm) *plus* long wavelength cut–off dichroic coating (λ/2=5490 nm)

g) *Field positions*

The modulation transfer factor should be measured at three positions in the image field (*Fig. 4*)[1]:

- *position 1:* on axis;
- *position 2:* off axis, on a circle of radius equal to 0.25 times the image diagonal;
- *position 3:* off axis, on a circle of radius equal to 0.4 times the image diagonal;
- *position 4:* at the corners of the image.

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[1] In principle, owing to the change in picture width, the positions at which off–axis measurements are taken in the 16:9 aspect ratio should be slightly different to those adopted for the 4:3 aspect ratio. The change in positions is not considered significant, however, and can be ignored in practice.

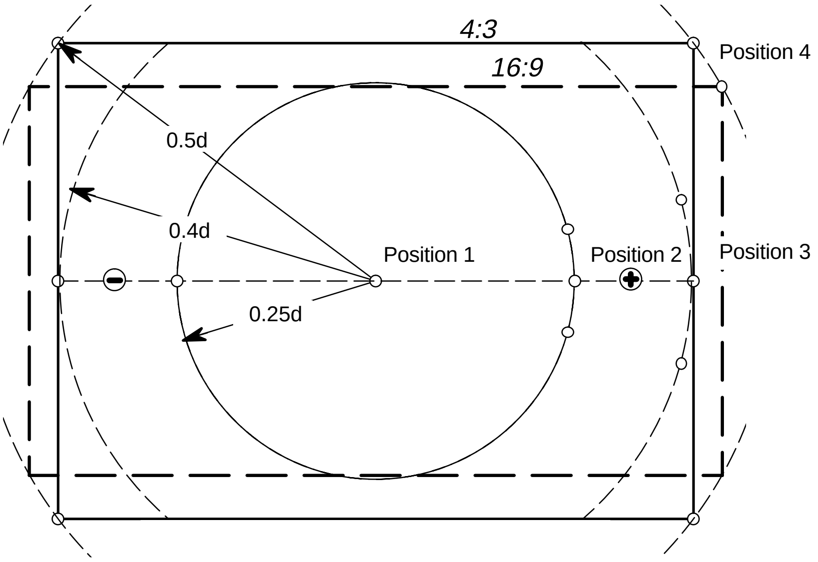


Fig. 4 – On–axis position (1) and off–axis positions (2, 3 and 4) in the image field, seen from behind the lens.

At each position, the modulation transfer factor is measured in both the radial and tangential directions with respect to the circles. Measurements are taken on both sides of the axis. Field positions are positive on the right–hand side, and negative on the left–hand side of the image plane, when viewed from behind the lens (as shown in *Fig. 4*).

Table 7 gives the dimensions of film image formats (camera aperture image) and the corresponding off–axis distances, and *Table 8* gives similar dimensions for television tube and CCD sensor sizes currently used by broadcasting organizations.

Table 7 – Dimensions of film camera apertures and off–axis distances.

Film gauge (mm)	**Image height** (mm)	**Image width** (mm)	**Image diagonal** (mm)	**Distance from centre of aperture** (mm)		
				Position 2	Position 3	Position 4
16	7.42	10.05	12.5	3.1	5	6.25
35	16	22	27.2	6.8	10.9	13.6

Table 8 – Dimensions of television camera apertures and off–axis distances.

Tube diameter (inches)	(mm)	**Image height** (mm)	**Image width** (mm)	**Image diagonal** (mm)	**Distance from centre of aperture** (mm)		
					Position 2	Position 3	Position 4
4:3 aspect ratio							
1 1/4	30	12.80	17.10	21.40	5.35	8.50	10.70
1	25	9.60	12.80	16.00	4.00	6.40	8.00
2/3	18	6.60	8.80	11.00	2.75	4.40	5.50
1/2	13	4.80	6.40	8.00	2.00	3.20	4.00
16:9 aspect ratio							
1	25	7.84	13.94	15.99	4.00	6.40	8.00
2/3	18	5.39	9.59	11.00	2.75	4.40	5.50

2.1.3. Presentation of results

It is recommended that the modulation transfer function of a zoom lens is presented as a function of focal length, having the on–axis and off–axis field positions as parameters; data for each side of the axis, and for radial and tangential measurements, should be assigned to separate curves on the graph. As the modulation transfer function is also dependent on the operating aperture and the spatial frequency, a large number of graphs will be obtained for the full set of test conditions defined in *Section 2.1.2.* For a rapid evaluation it is sufficient to have just one graph showing the modulation transfer factors as a function of focal length for different field positions (one side of the axis only), for the nominal aperture listed in *Table 1* and *Table 2* and for the actual cut–off frequency.

An example of the recommended form of graph is shown in *Fig. 5*. The MTF axis should be linear and the focal length axis logarithmic.

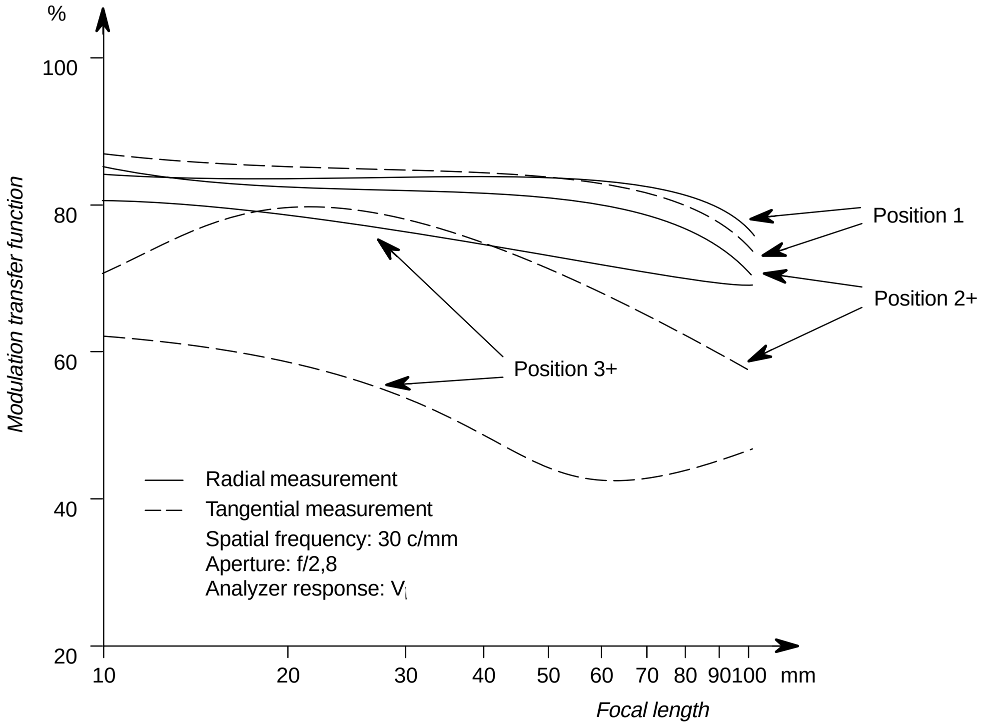


Fig. 5 – Modulation transfer factor as a function of focal length
(example for a zoom lens used with a 16–mm film camera).

2.1.4. Performance targets

Fig. 6 shows graphs of the MTFs of typical lenses which give acceptable picture sharpness for their intended applications. The MTFs are the average values of the *R* and *T* components: (*R*+*T*)/2.

Film camera lenses

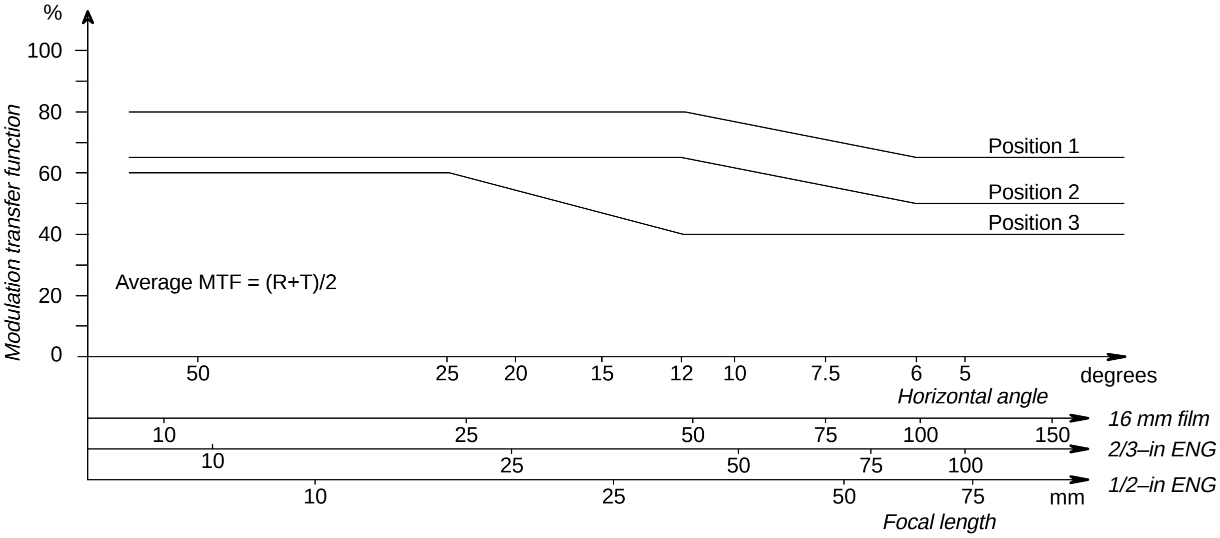
Fig. 6a) and *b)* show typical MTF curves for the two most–commonly used film gauges in television operations, 16 and 35–mm.

The MTF should be close to 86% over the full zoom range.

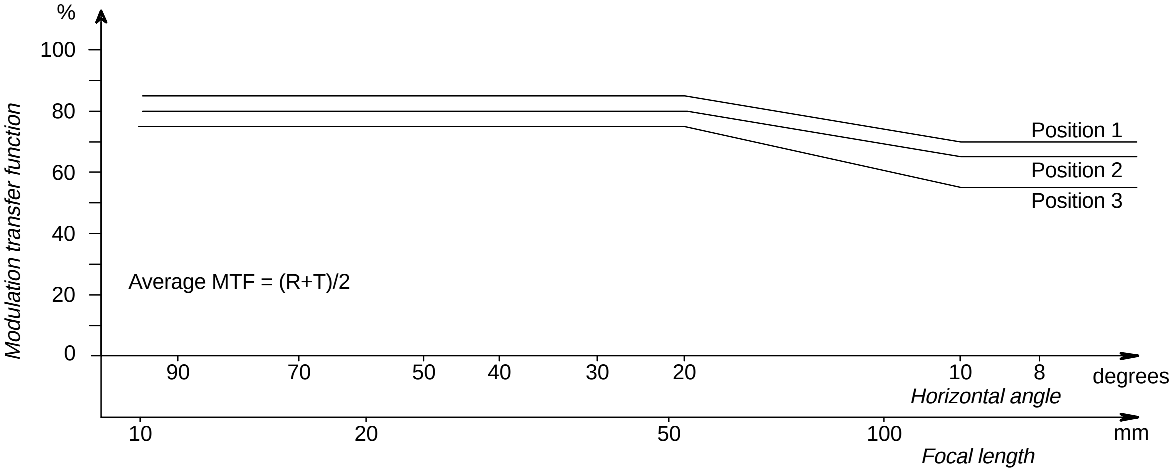
Television camera lenses

Fig. 6a) and *c)* show typical MTF curves of lenses for electronic news–gathering (ENG) and for television cameras intended for use in the studio and for outside–broadcasts. The curves are for the green channel. The MTF values for the red and blue channels should be at least 75% of those for the green channel.

a) Lens for a 16–mm film camera (photopic) or an ENG camera (green channel).



b) Lens for a 35–mm film camera.



c) Lens for a television camera (studio or outside–broadcast camera).

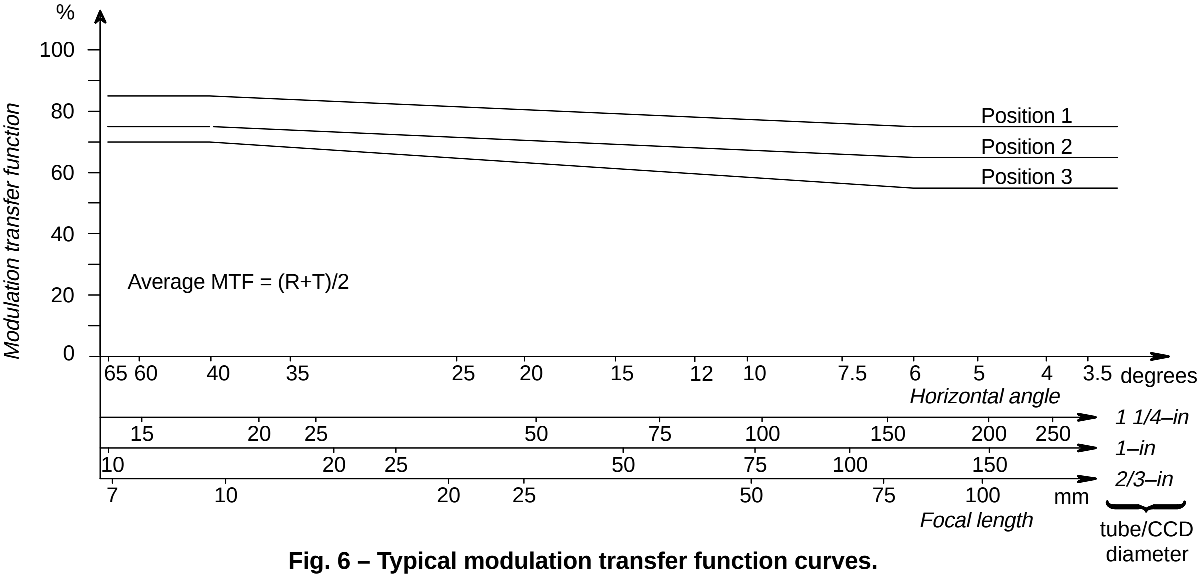


Fig. 6 – Typical modulation transfer function curves.

Film camera lenses	Television camera lenses
	“Full–facility” studio, outside–broadcast and electronic field–production lenses (see *Chapter 4, Section 4.1.1.*), should have an average MTF $((R + T / 2)$ of at least 85% on axis and 65% at field position 3 of *Fig. 4* (measurements at cut–off frequency, at nominal aperture, in the green channel and at twice the minimum focal length). The on–axis MTF should not fall below 80% over the full zoom range. A typical lightweight lens for electronic news–gathering will have an MTF of 75% (measured at cut–off frequency, at twice the minimum focal length and at an aperture of f/2.0). The maximum value of the astigmatism, expressed as the difference $\lvert R–T \rvert$ at the nominated aperture, is expected to be less than 5% for on–axis measurements and less than 30% for off–axis measurements (position 3, see *Fig. 4*) in a typical lens.

2.1.5. Equipment for MTF measurements

Draft International Standard DIS 9335 [7] gives guidance on the construction and use of equipment for the measurement of the optical transfer function of imaging systems in general. It specifies important factors that may influence measurement results and gives general indications regarding the performance of test systems as a prerequisite for accurate measurements. All the specification for the measurement of MTF given in the present document are in principle based on this ISO Standard, but with some adaptation to suit the specific applications of camera lenses for television.

Four measuring systems are known to be suitable for the measurement of film and television camera lenses according to the methods described in this document:

a) EROS IV Optical Bench

This system is made by Ealing Corp. of the USA, and is available through the company’s agents, Ealing Beck Ltd., Watford, England.

It is a research test bench capable of measuring all types of lenses to the highest degree of accuracy (MTF ± 0.02). The cost and size of this equipment puts it outside the scope of most lens users, and it requires highly–skilled and trained operators.

b) EROS 200 Optical Bench

This is a similar type of equipment to the EROS IV, but is smaller and achieves a slightly lower degree of accuracy, although it certainly remains adequate for the measurement of television and film lenses. The larger broadcasting organizations with some research facilities, and the lens manufacturers, would have this type of equipment. It required skilled operators.

c) Solid State EROS

This system uses the same mechanical and optical modules as the EROS 200 system, except for the analyzer/detector. A CCD line sensor is used to detect the line spread function produced by the lens under test. A personal computer is then used to calculate the MTF and the PTF. The system is menu–driven from the PC but still requires a skilled operator.

d) SIRA Lens Testing System

This equipment is manufactured by the Sira Institute Ltd., Chislehurst, Kent, England.

The equipment is especially designed to measure film and television camera lenses. It comprises four modules which do not need an optical bench or a permanent location. The system does not offer the range or the absolute accuracy of the research equipment, but will give a good check of the optical performance of a lens.

2.2. Flange focal distance / Back focal distance

To achieve interchangeability between lenses and cameras, the flange (back) focal distance must be kept within tight tolerances.

Film camera lenses

The flange focal distance is a very significant parameter for film camera lenses because it is the only mechanical assurance that the focal plane coincides with the film plane when the lens is mounted on the camera. This is especially important when taking scenes with “high–speed” lenses, for which the depth of focus is considerably reduced, even at full aperture; in such circumstances even a small mis–alignment of the flange focal distance would cause a perceptible degree of de–focus.

Television camera lenses

For studio and outside–broadcast camera lenses it is not so important to keep the tolerances of the back focal distance within such narrow limits as for film camera lenses. In electronic three–tube cameras the back focus can be adjusted individually for each colour channel. However the back focal distance must be constant at all focal lengths and all focus settings.

If interchangeability is required between lenses and cameras, as is the case for ENG operations, the back focal distance must be set to reasonable tolerances.

Note: For CCD cameras the tolerances on back focal distance may have to be tighter.

2.2.1. Definition

Film camera lenses

The flange focal distance is the distance between the plane of the flange mounting surface and the plane in which the modulation transfer factor, for a spatial frequency of 50 c/mm, is optimum, within an on–axis image whose object is at infinity.

Note: The optimum focal plane depends on the chosen focussing frequency. The reason for increasing the spatial frequency above the cut–off, in the case of film camera lenses, is that the technical performance of film productions for television is currently checked by projecting the film. In this situation, the higher frequencies have an important influence on the perceived picture sharpness. Also, the film cameraman normally adjusts the sharpest focus through the viewfinder by optimizing for the higher frequencies.

Television camera lenses

The back focal distance is the distance from the point of intersection of the optical axis with the back surface of the lens and the plane in which the modulation transfer factor for the cut–off frequency (see *Table 2*) is optimum, within an on–axis image whose object is at infinity.

2.2.2. Measurement conditions

Two different methods are currently used for the objective measurement of the flange or back focal distance of camera lenses. One method involves the application of the principle of the MTF (see *Section 2.1.*), the other involves an autocollimator. Although the second method does not correspond exactly to the definitions given in *Section 2.2.1.*, it has the advantage that the measurement procedure is more convenient and, for routine checks, it can even be conducted with the lens mounted on the camera. If done with a film running in a film camera, the method takes account of the overall lens/camera/film combination.

The measurements should be carried out as follows:

Film camera lenses

- in air at a spatial frequency of 50 c/mm, if the MTF principle is to be applied;

Television camera lenses

- with simulation of the glass path of the green channel, at the cut–off frequency (see *Table 2*), if the MTF principle is to be applied;

- on axis;
- at infinity;
- at minimum focal length (for zoom lenses);
- under the spectral conditions defined in *Section 2.1.2.f)*;
- with the lens in a horizontal position, and precisely mounted.

The focal length of the collimator lens should be between 4 and 12 times the focal length of the lens under test. This is to ensure adequate adjustment precision. The diameter of the collimated beam should at least fill the front element of the lens under test. The measurement accuracy should be equal to or better than 2 µm.

2.2.3. Presentation of results

Film camera lenses	Television camera lenses
The flange focal distance in air shall be indicated in millimeters.	The back focal distance, allowing for a specified glass path length in the green channel, shall be indicated in millimeters.

2.2.4. Performance targets

Film camera lenses	Television camera lenses
EBU specification The flange focal distance shall not deviate from the nominal value by more than ± 5 µm, at minimum focal length.	Back focus adjustment is normally provided for television camera lenses; a variation of about ± 0.5 mm is obtained by moving parts of the lens. The locking device must be operationally reliable. It is important that the manufacturer's specifications for the differences between the flange focal distances for the red and green channels, as referred to the green channel, should be within the tolerances mentioned in *Sections 2.5.4.* and *2.6.4.*

2.2.5. Equipment for measurement of flange or back focal distance

Film camera lenses	Television camera lenses
If a high degree of reproducibility in required, the Möller–Chrosziel test bench is suitable. This equipment applies the autocollimator principle and can also be used for precise adjustment of the ground–glass plate in the camera viewfinder. The equipment is manufactured by A. Chrosziel Film–Technik, Munich, Germany.	The Sira MTF test bench (see *Section 2.1.5.d)*) or equivalent can be used.

A special measuring system (flange focal distance tester) enables the flange focal distance of film cameras and the back focal distance of television cameras to be determined automatically. It uses the MTF principle and is manufactured by Carl Zeiss, Oberkochen, Germany.

2.3. Zoom tracking errors – axial

The image plane of the lens should either coincide with the light–sensitive layer of the film, or with the active layer of the pick–up tube or CCD sensor. If this coincidence is not maintained over the full zoom range, the focus will be lost at various points in the zoom range. This will be apparent in the graphs of MTF.

2.3.1. Definition

The axial zoom tracking error is an axial shift of the back focus as a function of the focal length.

2.3.2. Measurement conditions

The conditions for the measurement of the variations of the optimum focal plane with the focal length are the same as for the measurement of the flange or back focal distance (*Section 2.2.2.*). The flange/back focal distance should be the same for long and short focal lengths.

2.3.3. Presentation of results

The axial zoom tracking error should be shown as a graph of error (in millimeters, with a linear scale) against focal length (logarithmic scale). An example is shown in *Fig. 7*.

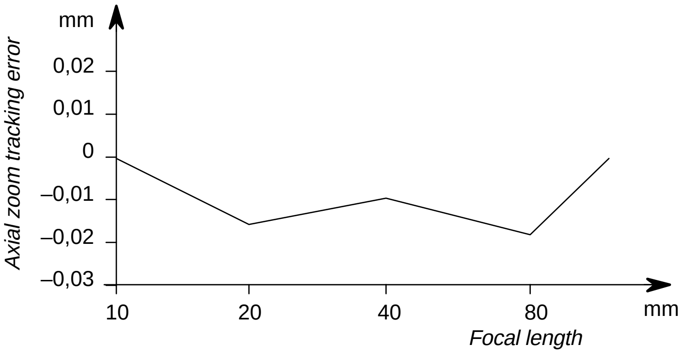


Fig. 7 – Axial zoom tracking error as a function of focal length
(example for a film camera lens).

2.3.4. Performance targets

Film camera lenses

EBU specification

The axial zoom tracking error shall not exceed 30 µm over the full range of operation of the zoom (for zoom ratios less than or equal to 1:12).

Television camera lenses

EBU specification

The axial zoom tracking error for a television camera lens (2/3–inch tubes) shall not exceed, in the green channel, the values in the *Table* below, over the full range of operation of the zoom. This specification should be respected over a zoom ratio of less than or equal to 1:12 (4:3 aspect ratio systems) or 1:14 (16:9 aspect ration systems). For other sensor sizes, the tracking errors should be in proportion.

Focal length (mm)	Displacement (µm)
minimum to 15	±10
>15 to 50	±15
>50 to maximum	±20

2.3.5. Equipment for measurement of axial zoom tracking error

The equipment required is the same as for the measurement of the absolute back or flange focal distance, indicated in *Section 2.2.5.*

2.4. Zoom tracking errors – lateral

2.4.1. Definition

The lateral zoom tracking error is a lateral shift of a point at the centre of the image, as a function of the focal length.

2.4.2. Measurement conditionsa)

The amount of zoom tracking error can be determined by measuring the lateral displacement of a reticule or a spot of light, while tracking the lens over the full range of focal lengths. The error should be tracked to zero at each end of the zoom range, and the displacement measured between these limits. The lens should be zoomed in both directions.

2.4.3. Presentation of results

The lateral zoom tracking error should be shown as a graph of the displacement, expressed as a percentage of the picture width with a linear scale, as a function of the focal length (logarithmic scale). An example is shown in *Fig. 8*.

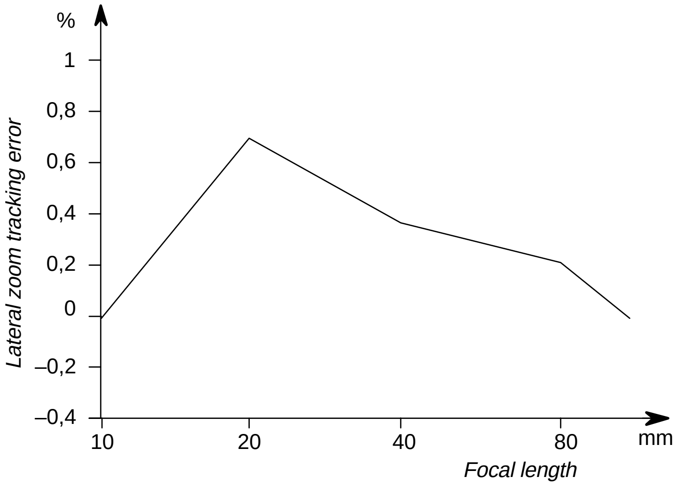


Fig. 8 – Lateral zoom tracking error as a function of focal length
(example for an ENG camera lens).

2.4.4. Performance targets

The alignment of the lens components shall be such that the centre of the image is not visibly displaced when zooming over the full zoom range.

EBU specification

The displacement of the centre of the image when zooming over the full zoom range, shall not exceed 1% of the picture width.

2.4.5. Equipment for measurement of lateral zoom tracking error

The equipment required is the same as for the measurement of the absolute back or flange focal distance, indicated in *Section 2.2.5.*

2.5. Chromatic aberrations – lateral

Chromatic aberrations can degrade the MTF of a lens and their most obvious effect is the appearance of coloured fringes at the edges of the picture. They can be separated into lateral components, considered in this *Section*, and longitudinal components considered in *Section 2.6.*

2.5.1. Definition

Lateral chromatic aberration is a wavelength–dependent radial displacement of the image of a point in the object plane, when imaged at the image plane. As a result of this aberration, the red, green and blue images in a television camera are formed at different positions relative to the optical axis and the effect is seen as colour fringing.

2.5.2. Measurement conditions

The severity of lateral chromatic aberrations can be determined by measuring the lateral change of a spot of light, or a narrow slit, when the light path is interrupted with a series of filters of different colours.

The following test conditions are recommended:

Film camera lenses	Television camera lenses
a) Glass block	
No glass block.	The glass block used to simulate the prism splitter block etc. of the camera must be inserted.
b) Colour filters	
Colour filters should be used which approximate the spectral sensitivity of the detector to the colour sensitivities of average film stock (see *Fig. 9*).	Colour filters should be used which approximate the spectral sensitivity of the detector to the colour–matching functions (positive lobes) corresponding to the picture tube primaries specified by the EBU (*Fig. 10*).

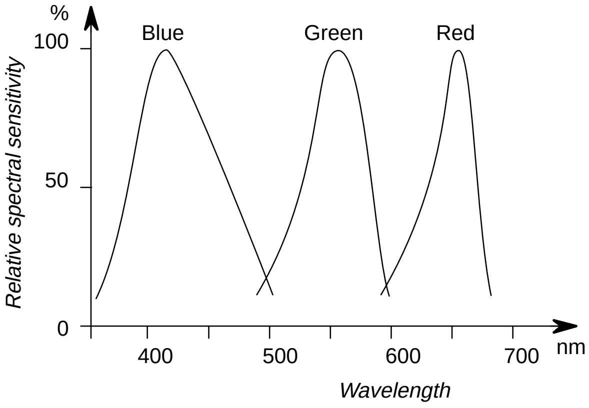


Fig. 9 – Average sensitivity of colour films used in television.

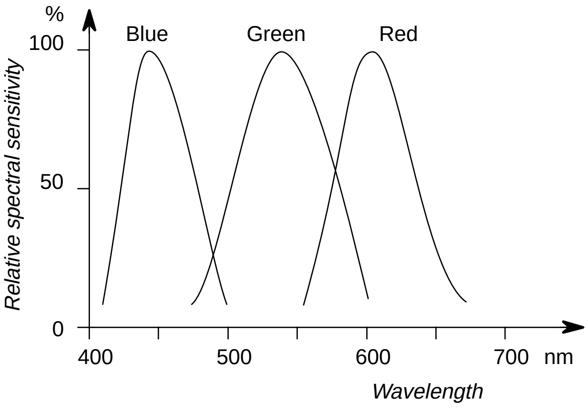


Fig. 10 – Colour matching functions (positive lobes) of a television camera conforming to the EBU primaries.

Table 4 lists a selection of practical filters which can be used to approximate the ideal curves for an S20 detector for measurements on film camera lenses. *Table 5* gives similar data for conventional definition television camera lenses (4:3 and 16:9 aspect ratio), while *Table 6* gives filter data for HDTV camera systems.

c) *Aperture*

The aperture should be set to the nominal aperture (see *Table 1* or *Table 2*), plus one stop.

d) *Focal length*

In the case of a zoom lens, the following focal lengths should be used:

- minimum;
- maximum;
- intermediate positions obtained by doubling the minimum focal length until the maximum is reached.

If range extenders or other lens attachments are fitted, the tests should be repeated under extreme conditions (it may be necessary to re–adjust the front focus.)

e) *Field positions*

Measurements are taken at position 3 (see *Fig. 4*), on a circle of radius equal to 0.4 times the image diagonal, and on both sides of the axis.

Note: It may be difficult to measure the lateral chromatic aberration because of blurring of the image. It may be helpful to measure either the light intensity or to take a position mid–way between positions at which the light intensity falls to 50% of the peak value.

2.5.3. Presentation of results

The amount of lateral chromatic aberrations should be indicated in terms of the lateral displacement measured in the red and blue channels, with respect to the green channel. This displacement, expressed in microns (µm, positive values indicating displacement away further away from the optical axis, negative values closer to the axis) should be plotted on a linear scale as a function of the focal length (logarithmic scale), for the specified field position and aperture. *Fig. 11* shows an example of this form of presentation.

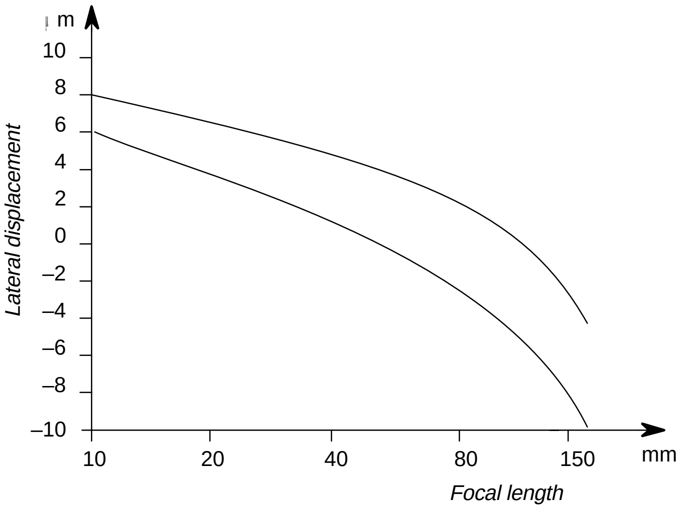


Fig. 11 – Lateral chromatic aberrations as a function of focal length
(example for a television camera lens).

2.5.4. Performance targets

It is necessary to have tighter tolerances on lenses for CCD cameras because these cameras do not have error compensation facilities. This is especially important for chromatic aberrations (both lateral and longitudinal) because dynamic registration compensation is not possible in CCD cameras.

Film camera lenses

For film camera lenses it is important to keep the lateral chromatic aberrations within close limits because they have an objectionable effect on the picture (coloured fringes) which cannot be compensated afterwards.

For a good film camera lens it can be expected that the relative displacement of the red and blue images, with respect to the green image, at field position 3 (see *Fig. 4*) and for the nominal aperture, will not exceed the figures given in the *Table* below.

Focal length (mm)	**Displacement (µm)**	
	16–mm film	35–mm film
minimum to 25	±5	±10
>25 to maximum	±10	±20

Television camera lenses

In a *three–tube television camera* the lateral chromatic aberration of a lens causes effects which are analogous to registration errors. They can therefore be corrected electronically.

For these cameras a certain displacement of the red and blue images with respect to the green image can be tolerated, provided that the displacement is constant with focal length, iris and focus settings.

This constant displacement, measured for position (see *Fig. 4*) and an the nominal aperture of a good lens should not exceed the figures given in the *Table* below. The variation of the red and blue displacements (with respect to the green) should not exceed one–half of the figures given in the *Table* over the entire zoom range.

Tube diameter		**Displacement**
(inches)	(mm)	(µm)
1 1/4	30	12.8
1	25	9.6
2/3	18	6.6
1/2	13	4.8

The image size of a *CCD television camera* cannot be adjusted electronically so no initial displacement can be tolerated.

EBU specification

In lenses used with CCD cameras having 2/3–inch sensors, any deviation of the red and blue images with respect to the green image shall be less ± 5 µm over the full range of the zoom. For cameras with other image (CCD) sizes, the tolerances shall be in proportion.

In lenses used with HDTV CCD cameras using 1–inch sensors, any deviation of the red and blue images with respect to the green image shall be less than ± 3 µm over the full range of the zoom. For cameras with other images (CCD) sizes, the tolerances shall be in proportion.

2.5.5. Equipment for the measurement of lateral chromatic aberrations

Any of the systems listed in *Section 2.1.5.* may be used for the measurement of lateral chromatic aberrations, provided they are fitted with the necessary micrometer measurement slides and a suitable selection of colour filters.

2.6. Chromatic aberrations – longitudinal

2.6.1. Definition

Longitudinal chromatic aberration is a wavelength–dependent axial displacement of the image of a point in the object when imaged at the image plane. This causes colour–tracking errors, especially at long focal lengths of zoom lenses with high zoom ratios. Excessive longitudinal chromatic aberration will impair the picture sharpness and cause colour halation.

2.6.2. Measurement conditions

The severity of longitudinal chromatic aberrations can be determined by a process involving the MTF measurement principle. A record is made of the axial movement of the image plane which is necessary in order to achieve accurate re–focussing of the image of the test image when the colour filters are changed. The reference plane is that which coincides with the best focus that can be obtained in the green channel, for the focal length under consideration.

The following test conditions are recommended:

Film camera lenses	Television camera lenses
a) Glass block	
No glass block.	The glass block used to simulate the prism splitter block etc. of the camera must be inserted.
b) Colour filters	
Colour filters should be used which approximate the spectral sensitivity of the detector to the colour sensitivities of average film stock (see *Fig. 9*).	Colour filters should be used which approximate the spectral sensitivity of the detector to the colour–matching functions (positive lobes) corresponding to the picture tube primaries specified by the EBU (*Fig. 10*). Filter data for use in HDTV camera systems are given in *Table 6*.

c) Aperture

The aperture should be set to the nominal aperture (see *Table 1* or *Table 2.*).

d) Focal length

In the case of a zoom lens, the following focal lengths should be used:

- minimum;
- maximum;
- intermediate positions obtained by doubling the minimum focal length until the maximum is reached.

If range extenders or other lens attachments are fitted, the tests should be repeated under extreme conditions (it may be necessary to re–adjust the front focus.)

e) Field positions

Measurements are taken on the optical axis, at position 1 (see *Fig. 4*).

2.6.3. Presentation of results

The amount of longitudinal chromatic aberrations should be indicated in terms of the displacement measured in the red and blue channels, with respect to the green channel. This displacement, expressed in microns (µm) with positive values indicating displacement towards the object, negative values further away from the object should be plotted on a linear scale as a function of the focal length (logarithmic scale). *Fig. 12* shows an example of this form of presentation.

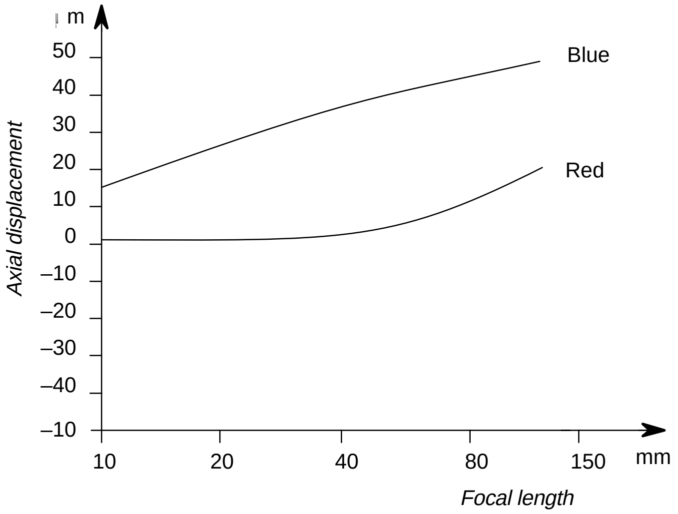


Fig. 12 – Longitudinal chromatic aberrations as a function of focal length
(example for an ENG camera lens).

2.6.4. Performance targets

Film camera lenses

For a good film camera lens the axial tracking error of the red and blue focal planes, relative to the green focal plane, should not exceed ±5 µm at minimum focal length and ±25 µm at maximum focal length.

Television camera lenses

EBU specification

The axial tracking error of the red and blue focal planes, relative to the green focal plane, shall not exceed ±5 µm at minimum focal length and ±25 µm at maximum focal length.

These tolerances apply to three–tube cameras using 2/3–inch tubes. The tolerances for other tube sizes shall be in proportion.

Note: Current models of CCD camera have defined offsets of the red and blue sensors with respect to the green sensor [4]. The image positions in these cameras cannot be adjusted mechanically. When measuring the longitudinal chromatic aberration of lenses for this sort of camera the offsets must be taken into consideration.

2.6.5. Equipment for the measurement of longitudinal chromatic aberrations

Any of the systems listed in *Section 2.1.5.* may be used for the measurement of longitudinal chromatic aberrations, provided they are fitted with the necessary micrometer measurement slides and a suitable selection of colour filters.

2.7. Spectral transmittance

Film camera lenses

The spectral transmittance of lenses for film cameras is of great importance if accurate colour rendering is to be obtained. This is especially true when shooting with colour–reversal film and no subsequent colour correction is applied. In particular, for daylight film types, the colour balance of the resulting picture will depend on the exact shape of the spectral transmittance characteristic of the lens in the blue and near–ultraviolet region, because most film emulsions are especially sensitive at these wavelengths.

Television camera lenses

The shape of the spectral transmittance characteristic of lenses for colour television cameras is less important because the colour can be balanced electronically. However, it is desirable for the transmittance to be high throughout the visible spectrum because this contributes to the overall sensitivity of the lens/camera combination.

2.7.1. Definition

The axial spectral transmittance factor of a camera lens is the ratio of the radiant flux of wavelength λ transmitted by the object to the radiant flux of wavelength λ that reaches the film or pick–up device, in an axial beam of light passing though the lens [8].

2.7.2. Measurement conditions

Suitable measurement procedures for the spectral transmittance of lenses are described in [8]. In particular the following conditions must be fulfilled:

- the beam of light must be co–axial with the optical axis of the lens and the beam diameter must be one–half of the diameter of the entrance pupil of the lens;
- the wavelength range must be from 350 to 700 nm;
- the wavelength should be incremented in steps of no more than 10 nm;
- the detector bandwidth must be less than or equal to the wavelength increment;
- the detector must be sufficiently sensitivity to all wavelengths in the range from 350 to 700 nm;
- the spectral reflectance of the diffusing paint on the internal surfaces of the integrating sphere shall be as high and as non–selective as possible , over a wavelength range from 350 to 700 nm;
- care must be taken to ensure that room lighting and light from the source do not enter the detector; the use of a double monochromator is recommended.

2.7.3. Presentation of results

The spectral transmittance should be presented in the form of a graph of the relative transmittance factor, (expressed as a percentage) as a function of the wavelength. *Fig. 13* shows an example of this presentation.

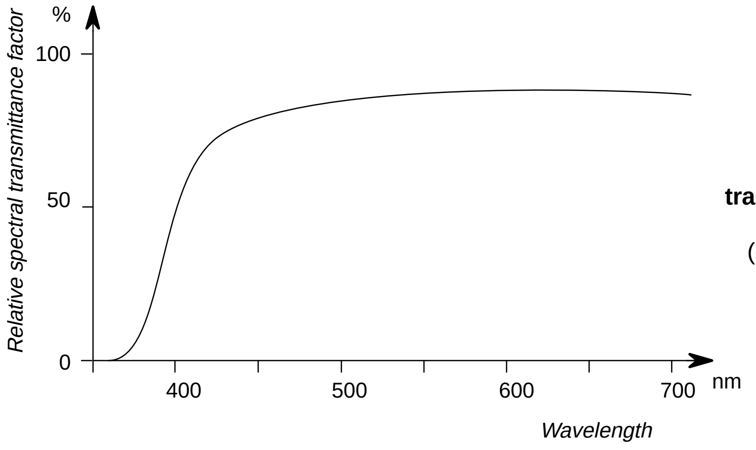


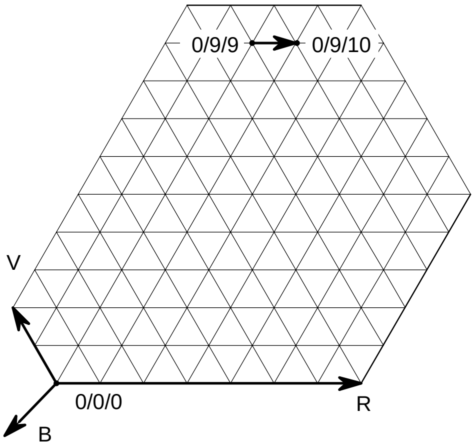
Fig. 13 – Relative spectral transmittance factor as a function of wavelength
(example of a zoom lens for film cameras).

Film camera lenses

For film camera lenses, the ISO colour contribution index (CCI) should also be determined. This method of assessing the contribution of spectrally–selective film camera lenses to the colour balance of the final film image is described in [9]. The resultant shift of colour balance, relative to that of a standard lens, is then represented in a tri–linear diagram (*Fig. 14*).

Television camera lenses

The ISO colour contribution index, CCI, is not applicable to lenses for television cameras.



0/9/9 : CCI of lens meeting EBU spec. (see *Section 2.7.4.)*

0/9/10 : CCI of zoom lens in *Fig. 13*

Fig. 14 – Presentation of the ISO colour contribution index, CCI
(example for the zoom lens of *Fig. 13*).

Note: A comparison of the average spectral sensitivity data for daylight films used in pictorial photography, on the one hand, and for television on the other hand, shows that there are substantial differences, especially in the near–ultraviolet region. When assessing the CCI it is therefore recommended that the weighted spectral sensitivity values W(λ) shown in *Table 9* of this document are used instead of the values given in Table 3 of [9].

Table 9 – Weighted values (W) of the spectral sensitivity for daylight films for colour television.

Wavelength λ (nm)	**$W_B(\lambda)$**	**Wavelength λ (nm)**	**$W_G(\lambda)$**	**Wavelength λ (nm)**	**$W_R(\lambda)$**
370	1	490	1	560	1
380	2	500	2	570	2
390	4	510	3	580	2
400	10	520	6	590	3
410	13	530	10	600	3
420	13	540	15	610	4
430	11	550	18	620	6
440	11	560	17	630	9
450	10	570	14	640	14
460	8	580	10	650	22
470	6	590	3	660	24
480	5	600	1	670	18
490	3			680	2
500	2				
510	1				

2.7.4. Performance targets

Film camera lenses

There is a practical requirement for a common spectral transmittance when different types of lens, including both fixed focal length and zoom types, are used to shoot the same subject.

EBU specification

The relative spectral transmittance shall conform to the diagram in *Fig. 15*.

Television camera lenses

The shape of the spectral transmittance characteristic is less important in the case of television cameras because the colour can be balanced electronically. However, high transmittance throughout the spectrum is desirable from the point of view of sensitivity.

Differences in the transmittance at wavelengths of 445 ns and 605 nm, relative to that at 540 nm, should not exceed 20%.

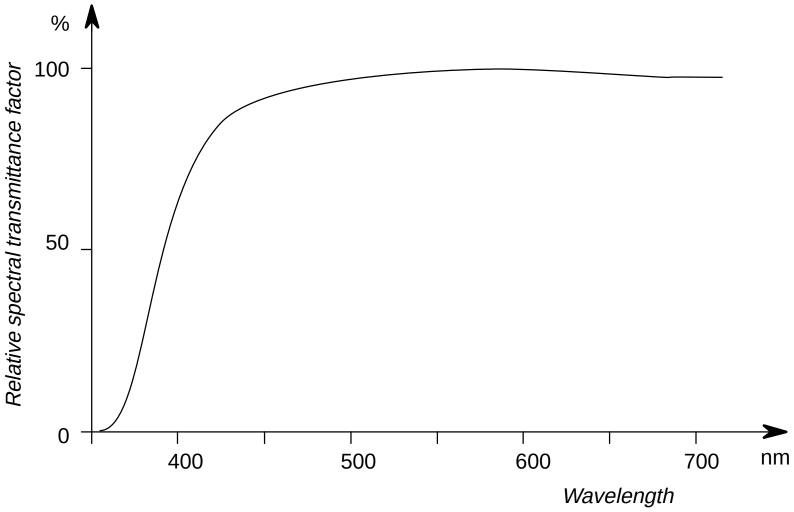


Fig. 15 – Spectral transmittance for lenses used for television film–making.

The resultant Colour Contribution Index (CCI) of this lens is 0/9/9 and it is recommended that all manufacturers adopt this as a target for lenses intended for use in television production.

Suggested tolerances are:

B = 0 (+2, –3)   G = 9 (+0, –2)   R = 9 (+0, –3)

These tolerances are illustrated by the hexagon in the tri–linear diagram in *Fig. 16*. All lenses with a CCI which lies within the hexagon may be used without any special precaution regarding visible colour casts.

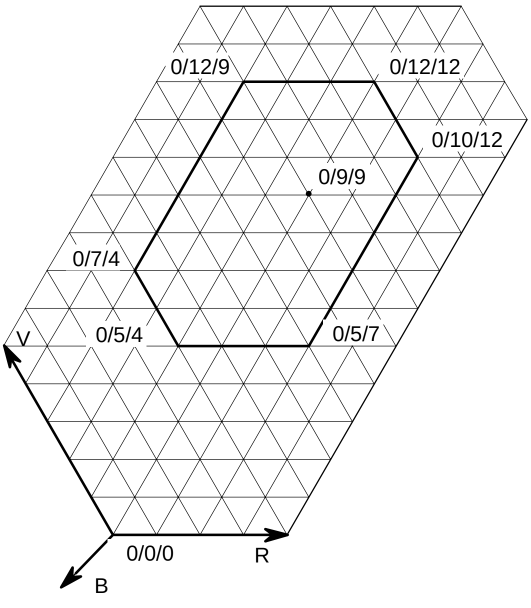


Fig. 16 – Recommended CCI of the film camera lens specified by the EBU.

2.7.5. Equipment for the measurement of spectral transmittance

There is at present no commercially–available complete equipment available for the measurement of this characteristic. Fig. 1 of [10] shows in detail a suitable arrangement of apparatus comprising a tungsten filament lamp, a monochromator, a collimator lens, an integrating sphere and a detector system. The necessary modules can be obtained from suppliers of optical equipment.

2.8. Transmission factor and aperture scales

The aperture scale of a lens is calibrated in relative aperture stop markings, known as *f–stops*, as determined by the geometric configuration of the lens. It gives an indication of the depth of field that can be obtained. However it does not give a measure of the light transmission. The optical transmission of a lens is important because it governs directly the amount of light reaching the film or pick–up device. Light is lost by absorption and surface reflection in its passage through a lens. Other effects such as vignetting and a natural decrease of field illuminance (see *Section 2.9.*) may further reduce the resultant light flux, especially in the corners of pictures taken with high–speed lenses operating at full aperture.

The maximum relative aperture of zoom lenses should be constant over the whole zoom range. In lenses which have a very wide zoom range, iris ramping may be unavoidable as the narrow–angle extremity of the range is approached.

Film camera lenses	Television camera lenses
This is of particular interest in the case of film camera lenses because it is the average illuminance over the full picture area which, together with the exposure time, governs the correct exposure of the film image. To ensure that colour film materials can be exposed correctly, and to permit lenses to be changed without problem, the film lens should be calibrated with photometrically–determined exposure stops, known as *e–stops*.	In contrast to a film camera lens, a change in the transmission of a television lens, and any shading effects, can be detected immediately and electronic compensation can be applied.

2.8.1. Definitions

a) *Relative aperture*

The relative aperture of a lens is the ratio of the diameter of the lens entrance pupil to the focal length [8].

b) *f–stop*

The stop number (commonly called the “f–stop”) is the reciprocal of the relative aperture.

c) *Transmission factor*

The transmission factor, τ, is the ratio of the light flux delivered from the back of the lens to the light flux incident upon the entrance pupil.

d) *T–stop*

The transmission stop (T–stop) is the ratio of the stop number, f, (determined from the geometrical configuration of the lens) and the square root of the transmission factor, τ :

$$T\text{–}stop = \frac{f}{\sqrt{\tau}} \qquad \textbf{(Eqn. 1)}$$

e) *e–stop*

The exposure stop (e–stop) is proportional to the square root of the luminance L (in cd/m2) of an object source, divided by the resultant average illuminance E (in lux) in the “action area” of the film image area [11].

$$e\text{–}stop = \frac{1}{2}\sqrt{\frac{L \times \pi}{E}} \qquad \textbf{(Eqn. 2)}$$

2.8.2. Measurement conditions

The relative aperture and the f–stop should be measured according to the procedures described in [8].

Film camera lenses

For the measurement of the e–stop of film camera lenses it is common practice to use an extended, uniformly–bright field with Lambertian emission as an object source. The average illuminance in the image plane is determined photometrically by integrating the light flux over the “action area” of the film format; the illuminance per unit area is then found. This procedure takes account of the optical transmission of the lens and of vignetting within the defined area of the film within which essential pictorial matter may be composed.

The spectral characteristics of the light source and of the detector should conform to the indication given in *Section 2.1.2.f)* (Vλ measurement). As the vignetting effects may be dependent on the actual focal length, the e–stop for zoom lenses should be determined mid–way between the minimum and maximum focal lengths.

Television camera lenses

The optical transmission factor of a television camera lens is determined in a direction parallel to the optical axis. A narrow beam of light, of diameter equal to one–half of the diameter of the entrance pupil of the lens, is used. The transmitted light is collected by an integrating sphere and measured. The transmission factor is determined as being the ratio of the measurement results with and without the lens in place. This procedure ensures that the effects of vignetting are ignored.

The transmission factor of a lens is measure at full aperture. The corresponding T–stop is then calculated from the transmission factor t and the geometrically–determined f–stop using *equation 1* (*Section 2.8.1.d)*).

To facilitate the accurate measurement of the T–stop scale of a lens, it is recommended that either a set of metal plates with accurately–sized circular holes is used, or a calibration lens with a standard aperture.

The spectral characteristics of the light source and of the detector should conform to the indications given in *Section 2.1.2.f)* (green channel measurements).

If fitted, measurements should be made with and without range extenders.

2.8.3. Presentation of results

The stop number of the maximum relative aperture should be given numerically (e.g. f/2.2). Also, the real f–stop numbers for each of the engraved markings (f/2.2 – 2.8 – 5.6 – 8 – 11 – 16, etc.) should be listed.

Film camera lenses

The e–stop number at full aperture and the f–stop numbers with the iris control position set at each engraved marking are presented numerically, as shown in the example below:

e–stop at full aperture	. . .
Engraved iris marking	**Measured f–stop**
f/2.2	f/2.1
f/2.8	f/2.7
f/5.6	f/5.3
f/8	f/7.4
f/11	f/10,3
f/16	f/15.8

Television camera lenses

For a zoom lens, a graph should be given showing the maximum T–stop for full aperture (linear scale) as a function of focal length (logarithmic scale) (*Fig. 17*).

If the transmission is constant across the full range of focal lengths, and no iris ramping effects are observed, it can be indicated as a single number (e.g. T/1.7).

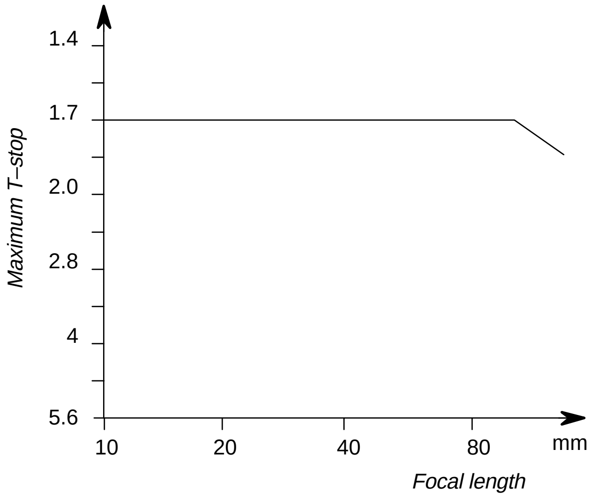


Fig. 17 – Variation of maximum T–stop as a function of focal length
(example for an ENG camera lens – the reduction at longer focal lengths is due to iris ramping effects).

2.8.4. Performance targets

Film camera lenses	Television camera lenses
The overall transmission factor of a good lens will exceed 70% and will not vary by more than 5% throughout the zoom range. To enable exact film exposure, the accuracy of the e–stops should conform to Draft International Standard ISO/DIS 8707 (tolerance of f–numbers).	For a good lens it is expected that the axial transmission factor will exceed 70% in the red and green channels and 65% in the blue channel, and that these values will not vary by more than 5% throughout the zoom range. There should be an engraved marker indicating the nominal aperture with an accuracy of ± 5%. The f–stop numbers and the maximum T–stop should also be marked. These markings should be easily visible when the lens is mounted on the camera.

Iris ramping will be minimized in a good lens.

It is desirable that the lens manufacturer provides information on the iris ramping characteristics.

2.8.5. Equipment for the measurement of transmission and aperture scales

Film camera lenses	Television camera lenses
For e–stop measurement, a stop–tester made by Steffelbauer, Munich, Germany is suitable. This measures the average illuminance in the picture gate and is supplied with a calibrated lens.	The transmission factor can be measured with a photometric device in a test bench similar to that used for the measurement of spectral transmittance (but without a monochromator in the path of the collimated light beam). Measurements can be taken with and without the lens and the results compared. The Sira Lens Testing System (see *Section 2.1.5.d)*) is also suitable for measurement of the transmission factor.

2.9. Relative field illuminance (white shading)

An important aspect of the design of camera lenses is the uniformity of illumination over the image area. Any un–evenness of the relative field illuminance is due to obstruction of the beam of light entering the lens as its obliquity increases. It may therefore be caused by mechanical obstruction of marginal rays (vignetting) or by the natural cosine–law of illumination. The effect is a reduction in image illumination away from the centre of the image plane, and it becomes especially apparent at full aperture.

The measurement of relative field illuminance provides a means of verifying white shading which could occur at the edges of the picture. It may vary with focal length and aperture setting; it becomes especially apparent at full aperture and is normally reduced by stopping down. For a zoom lens operating at the wide–angle end of the zoom range the centre of the image may be evenly illuminated but there is a rapid reduction in illumination towards the corners. At the narrow–angle end of the zoom range there is a gentle drop in illumination from the centre towards the edges of the picture.

2.9.1. Definition

The relative field illuminance is the ratio of the illuminance for off–axis field positions to the illuminance in the centre of the field, for an object of uniform illuminance.

2.9.2. Measurement conditions

It is recommended that measurements are taken under the following conditions:

- at full aperture and at the nominal aperture (see *Table 1* and *Table 2*);
- at the minimum object distance of the lens;
- with the focal lengths indicated in *Section 2.1.2.e)*;
- at the four field positions 1, 2, 3 and 4 shown in *Fig. 4.*;

Film camera lenses	Television camera lenses
– under the spectral conditions indicated in *Section 2.1.2.f)* (photopic eye response).	– under the spectral conditions indicated in *Section 2.5.2.b).*

2.9.3. Presentation of results

The ratio of the off–axis field illuminance to the on–axis field illuminance is plotted for selected focal lengths as a function of the field positions.

Film camera lenses	Television camera lenses
For film camera lenses, the relative illuminance is plotted for two different apertures (see *Fig. 18*).	For television camera lenses, the relative illuminance is plotted for each of the colour channels (see *Fig. 19*).

2.9.4. Performance targets

In an acceptable lens, the illuminance at position 4 of the image plane (the extreme corners, see *Fig. 4*) would be no less than 75% of the illuminance at the centre, at the nominal aperture.

2.9.5. Equipment for the measurement of relative field illuminance

The relative field illuminance is measured photometrically by imaging a uniformly–illuminated object source into the imaging plane and scanning the illuminance distribution with a suitable photometer. The relative field illuminance is given by comparison between the results obtained on–axis and off–axis. The Sira Lens Testing System (see *Section 2.1.5.d)*) can be used for this measurement.

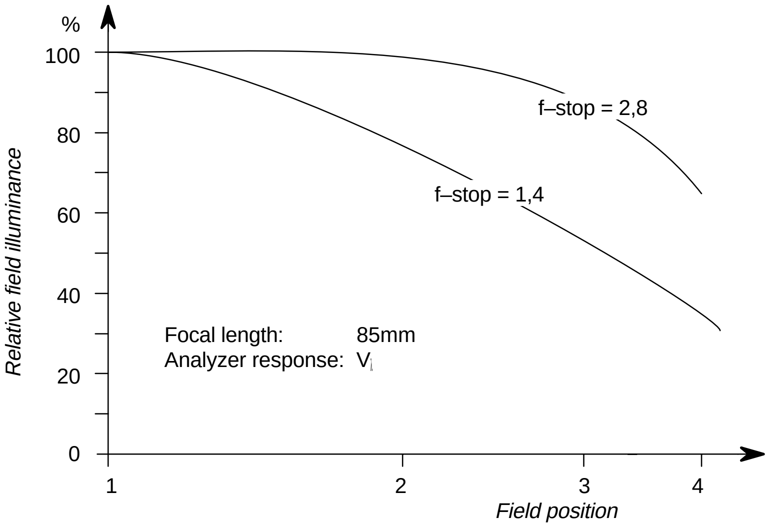


Fig. 18 – Relative illuminance as a function of field position, for two different apertures (film camera lens)**.**

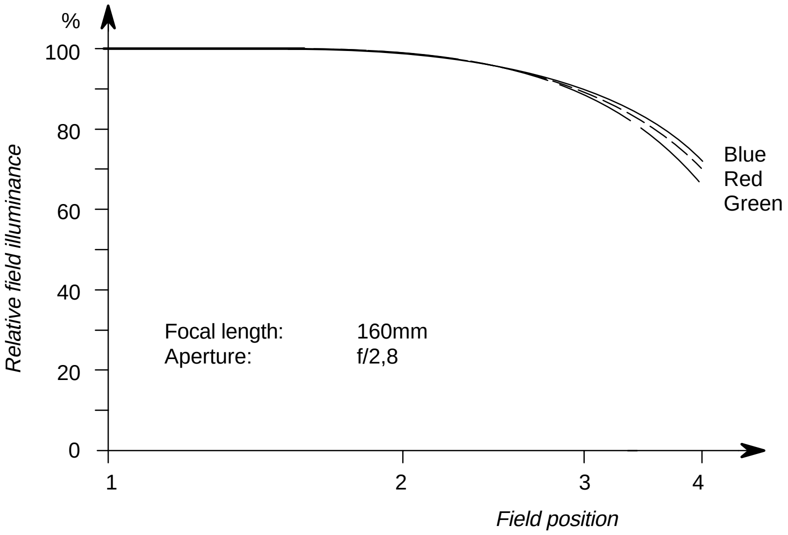


Fig. 19 – Relative illuminance as a function of field position, for the RGB channels (television camera lens)**.**

2.10. Veiling glare (flare)

Veiling glare (also commonly known as flare) is caused by light reaching the image plane as a result of scattering and reflections within the lens system.

This can have two main effects on the picture quality. The first is an increase in uniform veiling which would result in a reduction of the image contrast. The second is multiple imagery of bright sources due to multiple reflections in the lens surfaces and from sources outside the field of view (ghost images).

The prism splitter block of a television camera may introduce further flare errors. To take these errors into account, the whole system must be measured; this aspect is beyond the scope of the present document.

2.10.1. Definition

The veiling glare index is defined, for the purposes of the present document, as the ratio of the illuminance in the image of a black area and the illuminance in a surrounding bright field.

2.10.2. Measurement conditions

Two approaches to the measurement of veiling glare are possible, a differential method and an integral method.

The *differential*, or elementary source, method uses a small intense light source to illuminate the lens under test. The intensity distribution in the image plane is measured as the light source is moved throughout the object space. This method yields comprehensive information on the causes and effect of ghost images and on the distribution of glare in the image plane.

To facilitate the detection of ghost images, it is recommended that visual inspection is carried out on the image projected onto a translucent screen, while moving the light source within the acceptance hemisphere of the entrance pupil of the lens.

The disadvantage of the differential method is that the analytical scanning and evaluation are too time–consuming for use in an operational environment. This problem is avoided with the integral method.

The *integral*, or black spot, method is recommended for the verification of camera lenses [12]. It permits the determination of the general effects of veiling glare, in terms of a reduction in the image contrast, and gives an average numerical value representative of the glare performance.

Reproducible results can only be obtained if the test conditions are carefully standardized, and the procedure described below is recommended.

a) Surrounding bright field

The light source should have an extended size (preferably 2π steradians) and be of uniform illuminance at the entrance pupil of the lens under test. It should behave as a Lambertian emitter, as is the case, for example, with a diffusely–reflecting sphere or hemisphere. The illuminant should have a colour temperature of 3100 ± 100 K.

b) Black area

The black area should be circular and of size such that it produces an image whose diameter is equal to 0.1 ± 20% of the diagonal of the image format (for film cameras, the image format should be taken as equal to the transmitted area defined in [11]).

c) *Detector unit*

The measuring aperture must be circular and its diameter less than 0.2 times the diameter of the image of the black area.

Film camera lenses	Television camera lenses
The spectral sensitivity of the detector should simulate the CIE visual luminosity function V_λ (*Fig. 2*).	The spectral sensitivity of the detector should simulate the green channel response (*Fig. 3*). If it is of special interest to determine the tri–stimulus components of the glare index, it is recommended that the colour filters listed in *Section 2.5.2.b)* should be used.

d) *Object conjugate*

The object conjugate should be at least 10 times the focal length of the lens under test.

e) *Field positions*

Veiling glare is measured at the centre of the image plane (position 1 in *Fig. 4*) and at the corners (position 3).

f) *Aperture setting*

Veiling glare should be measured as a function of the aperture. Measurements should be taken at at least three settings: full aperture, minimum aperture and mid–way between full and minimum aperture.

g) *Focal length*

In the case of a zoom lens, the following focal lengths should be used:

- minimum;
- maximum;
- intermediate positions obtained by doubling the minimum focal length until the maximum is reached.

If range extenders or other lens attachments are fitted, the tests should be repeated under extreme conditions (it may be necessary to re–adjust the front focus.)

2.10.3. Presentation of results

For zoom lenses, the veiling glare factor, expressed as a percentage, should be plotted on a linear scale as a function of the focal length (logarithmic scale). Parameters for the curves are two apertures (full aperture and mid–way between full and minimum aperture), and selected spectral characteristics.

Veiling glare is also dependent on the field position, so two graphs are needed in order to give a comprehensive description of the performance of the lens, one for the on–axis position and the other for the corner of the image plane (*Fig. 20*).

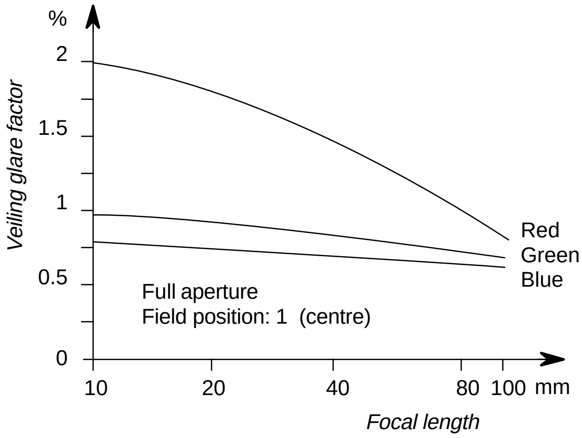


Fig. 20 – Veiling glare factor as a function of focal length
(example for an ENG camera lens).

2.10.4. Performance targets

In an acceptable lens, the veiling glare factor at field positions 1, 2 or 3 (see *Fig. 4*) measured under the appropriate conditions, should not exceed 2%.

2.10.5. Equipment for the measurement of veiling glare

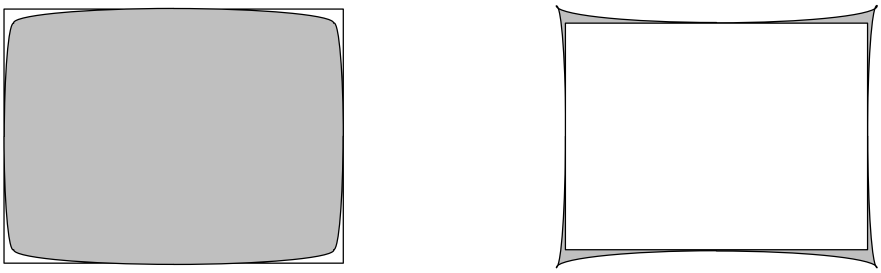
Any equipment built in accordance with the indications concerning either method discussed in *Section 2.10.2.* and suitable for measurements on lenses of large focal length will be both large and bulky. The Sira apparatus (see *Section 2.1.5.d)*) offers an alternative method which may be considered. A slide in the image plane carries a black spot of such a size that it completely obscures the image of a point light source. Any light which passes around the spot is detected and is a measure of the veiling glare of the lens.

2.11. Picture height distortion

Optical distortion is in general a variation of the magnification of the image which is dependent on the distance from the optical axis. The effect is to cause straight lines in the object to appear curved in the image. To suit the specific needs of television, it is the *picture height distortion*, rather than the more–general “distortion” defined by the ISO [13], which is determined by the measurement method presented here.

Two forms of geometric errors can be determined on a rectangular object (*Fig. 21*):

- a negative distortion, in which the points of the object are displaced from their theoretical position in a direction towards the optical axis (barrel distortion).
- a positive distortion, in which the points are displaced in a direction away from the optical axis (pincushion distortion).



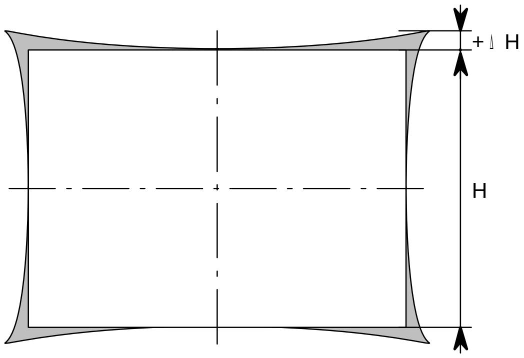
Barrel distortion (negative) Pin–cushion distortion (positive)

Fig. 21 – Illustration of geometry errors.

A zoom lens usually has negative (barrel) distortion at the wide–angle end of its zoom range, and positive (pin–cushion) distortion at the narrow–angle end. Zero distortion will occur at a zoom position somewhere between these extremes. These effects are especially evident in zoom lenses with high zoom ratios.

2.11.1. Definition

The picture height distortion is the largest positional shift ΔH of a corner of the image, in the vertical direction, expressed as a percentage of the actual height H of the image (see *Fig. 22*).



$$\text{Picture height distortion} = \pm \frac{\Delta H}{H}$$

H = height of final image

Fig. 22 – Picture height distortion.

2.11.2. Measurement conditions

The actual height of the image is adjusted to be equal to the height of the image format for the camera. The geometric displacement is measured in the four corners of a rectangular object having an aspect ratio of 4:3, and the average of the four results is calculated.

The recommended method involves the projection of the image of a calibrated graticule through the lens under test. The distance between the front of the lens and the projection screen should be 3 m.

For zoom lenses, the picture height distortion should be determined as a function of the focal length.

2.11.3. Presentation of results

For zoom lenses, the relative picture height distortion is plotted as a percentage, with a linear scale, as a function of the focal length (logarithmic scale), as shown in *Fig. 23*.

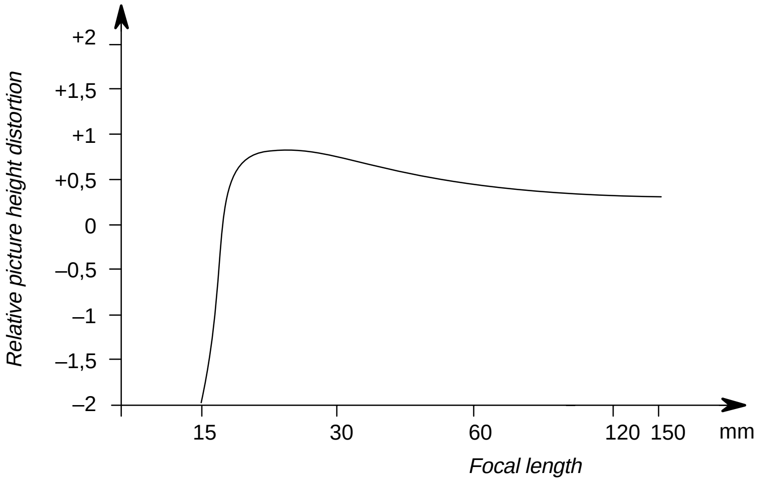


Fig. 23 – Picture height distortion as a function of focal length
(example for a television camera lens).

2.11.4. Performance targets

In order to prevent noticeable picture impairment, the measured values of picture height distortion shall be within the limits of –1% to +1%; this tolerance applies to all lenses except wide–angle types, for which a tolerance of –2% can be tolerated.

As a rule of thumb, 1% distortion is noticeable, although under certain critical conditions a distortion of 0.5% can be detected.

In principle, the tolerance on picture height distortion should be increased slightly in the case of systems operating in the 16:9 aspect ratio. The difference is not significant, however, and the limits set out above apply to all picture formats.

2.11.5. Equipment for the measurement of picture height distortion

A practical method of measuring picture height distortion is to use a precision graticule inscribed with a rectangle of the correct size, and projecting its image onto a marked screen with the lens under test. The Sira Lens Testing System (*Section 2.1.5.d)*) uses this method.

Chapter 3

Mechanical characteristics

Many of the optical characteristics described in *Chapter 2* are dependent to a greater or lesser extent on the mechanical aspects of lens design and manufacture. Zoom tracking error, for example, is a function not only of lens element design but also of the complex relative motions of the lens elements as the zoom angle is changed. Inadequacies in specific optical parameters may therefore be due to poor mechanical design, or inadequate manufacturing tolerances affecting the mechanical parts of the lens.

In addition to these opto–mechanical characteristics, there are a number of mechanical characteristics which must be considered, bearing in mind the specific uses made of a particular type of lens. In essence, these concern the adaptability of the lens to its working environment as regards noise generated by the mechanical sub–systems (focus, zoom, iris), and the “feel” of the lens when in the hands of the cameraman where smoothness of operation and reproducibility of lens settings are important considerations.

This Chapter describes measurement methods for three characteristics:

- acoustic noise;
- backlash;
- torque.

The overall acceptability of a lens may nonetheless depend on many factors other than these three characteristics. *Section 3.4.* below discusses some of these aspects.

3.1. Acoustic noise

The acoustic noise generated by zoom lenses and their control systems must not be disturbing to a member of a studio audience sitting near to the camera, nor to the viewer, in the form of background noise picked up by microphones. To satisfy these conditions, the acoustic noise must meet the specifications given below.

3.1.1. Definition

Acoustic noise is noise which is generated when adjusting the operational settings of a zoom lens.

3.1.2. Measurement conditions

The noise generated by the mechanical systems of a zoom lens will generally be dependent on the rate at which the focus, zoom and/or iris are changed, and whether they are changed simultaneously or separately. It is therefore suggested that measurements should be taken at the fastest speeds that the lens will allow.

Film camera lenses	Television camera lenses
Acoustic noise should be measured as a sound–pressure level in dB(A) under free–field conditions at a distance of 1 meter in any direction from the lens assembly. The measurement should be made with a sound level meter satisfying the requirements of IEC Publication 651 (type 1).	The measurements conditions are the same as for film camera lenses, except that the noise should be analyzed in 1/3–octave bands.

3.1.3. Presentation of results

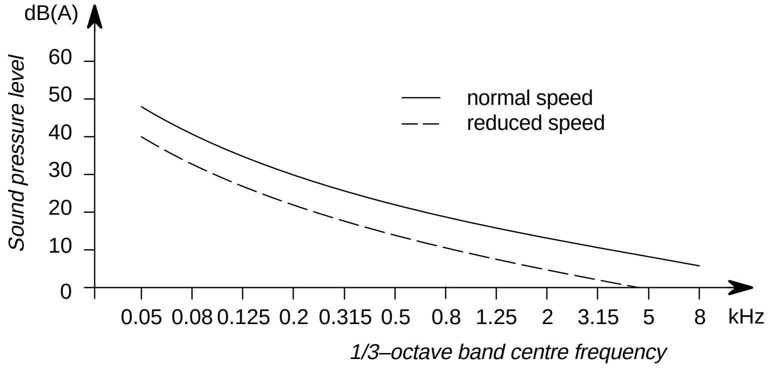
Film camera lenses	Television camera lenses
The sound pressure level is indicated in units of dB(A).	The results are shown in graph of sound pressure level (in decibels above $20\ \mu\text{N/m}^2$) as a function of the centre frequencies of the 1/3–octave bands.

3.1.4. Performance targets

Film camera lenses	Television camera lenses
EBU specification	*EBU specification*
The acoustic noise shall not exceed a level of 30 dB(A).	The acoustic noise in any 1/3–octave band shall be less than the limit shown in *Fig. 24* It may be necessary to reduce the zoom speed in order to meet this specification. Many ENG lenses will have a higher noise level.

3.1.5. Equipment for the measurement of acoustic noise

The use of the sound level meter type 2215 made by Brüel & Kjaer, Denmark, is recommended. This equipment is portable, easy to use and complies with the requirements of IEC Publication 179 for precision class instruments.



Note: Sound pressure in dB(A) above $(20\ \mu N/m^2)_{RMS}$
measured at a distance of one meter.

Fig. 24 – Maximum permitted noise level for zoom lenses in a television studio.

3.2. Backlash

In lenses, backlash causes positional errors when setting any of the control functions (zoom, focus, stops) when approaching the chosen setting from opposite directions. The effects of backlash will be especially evident after the lens has been in service for some length of time and the mechanisms are beginning to wear out. Backlash is usually manifest by transient variations in either the image position or the image quality.

3.2.1. Definition

Backlash is the lost motion between two elements of a mechanism, corresponding to the distance the first element has to move before communicating its motion to the second.

3.2.2. Measurement conditions

It is considered best to determine the acceptability of backlash in terms of the impact on these characteristics of the image quality, and the appropriate measurement methods will be found in *Chapter 2*.

3.2.3. Presentation of results

The presentation of the optical measurements results should conform to the prescriptions in *Chapter 2*.

3.2.4. Performance targets

The acceptability of backlash in zoom and focus mechanisms will depend on the severity of the degradation of the accompanying optical performance.

To achieve reliable and reproducible exposure, the backlash of the aperture adjustment should be less than ± 1/10 stop.

3.2.5. Equipment for the measurement of backlash

Backlash is evaluated indirectly, following the measurement of the optical performance of the lens.

3.3. Torque

It is important that the mechanism of the lens should move smoothly, with a uniform resistance throughout its range of travel. Abrupt changes of resistance make controlled movements of zoom and focus impossible.

3.3.1. Definition

Torque is the rotating moment exerted by a tangential force acting at a distance from the axis of rotation.

3.3.2. Measurement conditions

Film camera lenses (including lightweight ENG television lenses)

On most film and ENG camera lenses the zoom and focus movements are performed by rotating concentric sleeves on the body of the lens.

The torque required to rotate these sleeves can conveniently be measured by the torque reaction on the body of the lens.

Suitable equipment is mentioned in *Section 3.3.5.* It comprises a transducer display/power supply module (type D3A) and a base–mounted transducer (type ASL2b).

The lens is attached to the transducer head with its axis horizontal using an adaptor which is fitted to the lens mounting flange. The zoom control ring is rotated at uniform speed, taking about four seconds to complete its travel from one end of the range to the other. The movement is repeated while the zoom is moved in the other direction. The torque is recorded while the movement takes place.

The procedure is repeated on the focus control ring.

Television camera lenses (studio types)

Lenses with servo drive modules or controls driven through flexible drive–shafts can be checked by removing the drive modules and rotating the lens mechanism by hand. A special tool designed to engage with the mechanism will be required and if this is connected to an in–line transducer (type ASL2a from the manufacturer mentioned in *Section 3.3.5.* , used in conjunction with the display/power unit), the operating torque can be measured.

The lens should be in a horizontal position and the zoom control should be tracked from one end of its range to the other, and back again, taking approximately four seconds to complete each movement.

The procedure is repeated on the focus control.

3.3.3. Presentation of results

The extreme values of starting and running torque for the zoom and focus movements, in each direction, should be indicated in Newton–meters (nM).

3.3.4. Performance targets

The torque should ideally be in the range from 0.1 Nm to 0.25 Nm. The value should not vary more than 50% whilst moving across the full zoom range in either direction.

3.3.5. Equipment for the measurement of torque

The torque measurement apparatus referred to in *Section 3.3.2.* can be obtained from:

Adam Systems Ltd.
PO Box 15
Loughton
GB–Essex IG10 2NQ
United Kingdom.

3.4. Other mechanical considerations

It is not practicable to lay down specific mechanical tests for lenses because meaningful results can often be obtained only following long–duration tests on a number of samples; this approach is more applicable to mass–produced articles than it is to camera lenses which are manufactured in relatively small quantities.

This Section outlines the basic mechanical design philosophy which should apply to lens manufacture.

3.4.1. Class of work

In the case of all mechanical parameters which are not specified, it is assumed that they shall meet the requirements of “first class” optical and mechanical work. The constraints of this classification are laid down in the relevant professional standards.

3.4.2. Maintenance

The design should be such that maintenance requires a minimum of special equipment and can be carried out locally by skilled instrument mechanics. The manufacturer shall issue suitable maintenance instructions for this purpose. Great importance shall be attached to the ease of maintenance and to the availability of spare parts.

3.4.3. Operating conditions and reliability

A very high degree of mechanical and electrical reliability is essential. Any mechanism which controls the movements of the lens elements must be substantially free of backlash, and be both smooth and silent in operation. Particular attention should be paid to the take–up of movements of cascaded lens units, such as those employed in multi–range ganged zoom systems.

The lens and its control systems shall continue to work smoothly, normally and with no abrupt changes of operating torque or loss of optical performance when tilted away from the horizontal in any direction, within the full tilt range of the camera panning head (±75° in the case of studio or outside–broadcast lenses), and in any orientation in the case of ENG or EFP lenses.

The equipment may have to operate for some 4000 hours per annum, with periods of up to 12 hours of continuous use. This operation may be in the open air in all types of weather, in industrial atmospheres and sometimes in aircraft, fast–moving land vehicles or sea–going vessels. The construction shall be such that no malfunction of the equipment, either electrical, mechanical or optical, is caused by prolonged exposure to the above–mentioned conditions, and that such exposure shall not adversely affect the equipment. Long periods under intense studio lighting, in bright sunlight or under protective covers in rainy conditions shall not cause over–heating. The ambient temperature range shall be taken as –20°C to +55°C.

The use of lightweight materials in lens construction is to be encouraged, but their use should not necessitate more–frequent workshop adjustments nor prejudice the high standards of performance and reliability required.

Chapter 4

Lens types in relation to their intended applications

4.1. Television camera lenses

Television camera lenses can be divided into two broad categories: *full–facility* lenses for which the highest optical performance is required, and *lightweight* lenses for which some concessions are allowed. It may nonetheless be helpful to sub–divide the “full–facility” category into three groups: studio, outside–broadcast and electronic field–production (EFP) types.

The term “full–facility” is used here to describe a lens offering the following features:

- both the focus and the zoom can be operated via servo modules;
- one or more range extenders are incorporated and can be remotely selected;
- a pattern projector is available if required.

4.1.1. Full–facility lenses

a) Studio lenses

The most apparent differences between studio and lightweight lenses are their physical size and weight; a studio lens may be some 50 to 60 cm long and weigh about 30 kg. Since the total weight of a studio lens is roughly equally divided between its optical and mechanical components, the increased glass weight makes it possible to design a lens having a better optical performance than that attainable in lightweight lenses. This results in a sharper picture, and consequently a reduced requirement for electronic aperture correction in the camera. Studio cameras may have pick–up tubes which are larger than those in ENG/EFP cameras and this also reduces the demands on the lens design, making it easier to obtain good picture quality.

A larger lens can be designed with a larger zoom ratio (>15:1) whilst retaining acceptable picture quality. On the other hand, a zoom ratio in excess of 10:1 will normally lead to iris ramping effects causing the effective aperture to be reduced at longer focal lengths. To overcome this problem, the front–end diameter of the lens would have to be very large, thereby increasing the cost and weight beyond acceptable limits. For many large studio lenses, the maximum aperture is of the order of f/2, with a front diameter of 17 to 18 cm; ENG lenses have an aperture of f/1.4 to f/1.8, with a front diameter of 7 to 8 cm.

b) Outside–broadcast (OB) lenses

Lenses for OB usually offer the same optical performance as a studio lens, but their zoom range is shifted towards longer focal lengths and increased. These changes tend to increase both the weight and the size of the lens.

c) Electronic field–production (EFP) lenses

An EFP lens normally provides better picture quality than an ENG lens. The zoom range is usually larger and servo control of the zoom and focus is provided. This implies that an EFP lens is very similar to a full–facility lens, the essential difference being that they are intended for use with cameras using 2/3 or 1/2–inch tube or CCD sensors (which may also be fitted with ENG lenses).

d) Performance targets

Specific performance targets for full–facility lenses, in terms of modulation transfer function (MTF), are given in *Section 2.1.4.* of *Chapter 2*.

4.1.2. Lightweight lenses

As the emphasis here is on weight, usually between 1 and 3 kg, a compromise has be to made between optical performance, zoom range and aperture. The zoom range is often between 7:1 and 14:1, with a horizontal angle as wide as possible (55° for the 2/3–inch image format). Depending on the size of the pick–up tubes or CCD sensors, the maximum aperture should preferably be f/1.4, because ENG lenses are often used under poor lighting conditions. The minimum object distance should preferably be less than 1 meter.

Low weight, large zoom ratio (>10:1) and large aperture are all factors which will impose constraints on the optical performance. Low overall weight implies low glass weight and as a consequence limited possibilities for the correction of lens aberrations. In recent years the situation has improved with the development of new types of glass offering lower weight and a wider range of refractive indices and V numbers than were available in the past. Many ENG lenses have low resolution for off–axis points when operating at their maximum aperture, although this situation improves considerably when the lens is stopped down to apertures of the order of f/2.8 or smaller, because a smaller aperture excludes the marginal rays, improving the resolution. In general, lens aberrations increase as the aperture is increased.

A large zoom ratio makes it more difficult for the designer to minimize lens aberrations over the full zoom range. Lenses with large zoom ratios (>10:1) tend to exhibit astigmatism at longer focal lengths and this is indicated by differences between the radial and tangential values of the MTF for off–axis image points. Astigmatism does not depend on aperture, so image sharpness is not improved by stopping down the lens. Lenses with large zoom ranges will also have increased geometric distortion at extreme focal lengths.

Specific performance targets for lightweight lenses, in terms of modulation transfer function (MTF), are given in *Section 2.1.4.* of *Chapter 2*.

4.2. Film camera lenses

The requirements for film camera lenses are generally rather similar to those for television camera lenses, although the emphasis in favour of certain characteristics may be different. For example, chromatic errors, flare, deviations from the flange focal distance, spectral transmissions characteristics and aperture scales are much more important in film lenses than they are in television lenses. This is because these characteristics cannot be verified while shooting, and therefore immediate correction is not possible, in contrast to the situation in television cameras which are able to apply electronic compensation for certain optical defects of television camera lenses.

For the 16–mm film format, zoom lenses with a restricted zoom range of 10:1 to 15:1 are commonly used. The maximum aperture is about e/2.0 (see *Chapter 2*, *Section 2.8.1.e)*). Specific performance targets for film camera lenses, in terms of modulation transfer function (MTF), are given in *Section 2.1.4.* of *Chapter 2*.

For drama productions filmed for artistic reasons under low light levels, high–speed lenses having a maximum e–stop of about 1.5 are often used. Vignetting effects become apparent in the corners of the picture when using this sort of lens.

For feature film production in the 35–mm film format it is common practice to used fixed focal length lenses. These are expected to offer better optical performance than a zoom lens set to the same focal length.

Appendix

Analysis and interpretation of lens performance data

1. Introduction

Chapters 2 and *3* of this document have described measurement methods for 20 optical and mechanical characteristics of film and television camera lenses. Most of the methods – and those involving the measurement of modulation transfer functions in particular – will generate large quantities of test data which is likely to pose problems of analysis and interpretation.

The descriptions of the measurement methods have included recommended forms of presentation of results of individual measurements, usually in the form of tables or graphs. It nonetheless remains very difficult to interpret these results, and to determine what might be acceptable trade–offs between, for example, maximum aperture and astigmatism in a "high contrast" lens, or between weight and chromatic aberrations in an ENG camera lens.

In brief, the measurement data are of very considerable scientific significance but of relatively little practical use in the absence of a set of "rules of interpretation".

Ideally, it might be desirable to establish, for each major lens application described in *Chapter 4*, a "quality template" for each lens characteristic, or even a global "quality factor" taking account of all the measurement data and reducing it to a single figure. Such a form of presentation would be intended above all to make it easier for those who are not specialists in lens technology to make meaningful comparisons between lenses offered by manufacturers, to judge the severity of degradations of lens performance through ageing, or to select the most appropriate lens for any particular programme–making operation.

The diversity of parameters to be considered, and the probable difficulty of agreeing on template shapes or weighting factors for the paremeters included in a global quality factor conspire to make such an approach extremely difficult – if not actually impossible. It should not be forgotten that lens testing involves a certain amount of picture quality evaluation and this is an essentially subjective process.

The present Appendix nonetheless offers some ideas on two approaches to the problem, each addressing the problem from a different direction. The first is essentially a simple qualitative guide to the trade–offs in lens design, while the second examines ways of reducing measurement data to reasonable proportions through the application of statistical methods and computer processing.

2. Guide to lens parameter trade–offs

In purely qualitative terms, there is a trade–off between almost every characteristic of a lens, as described in *Chapters 2* and *3*, and its absolute quality.

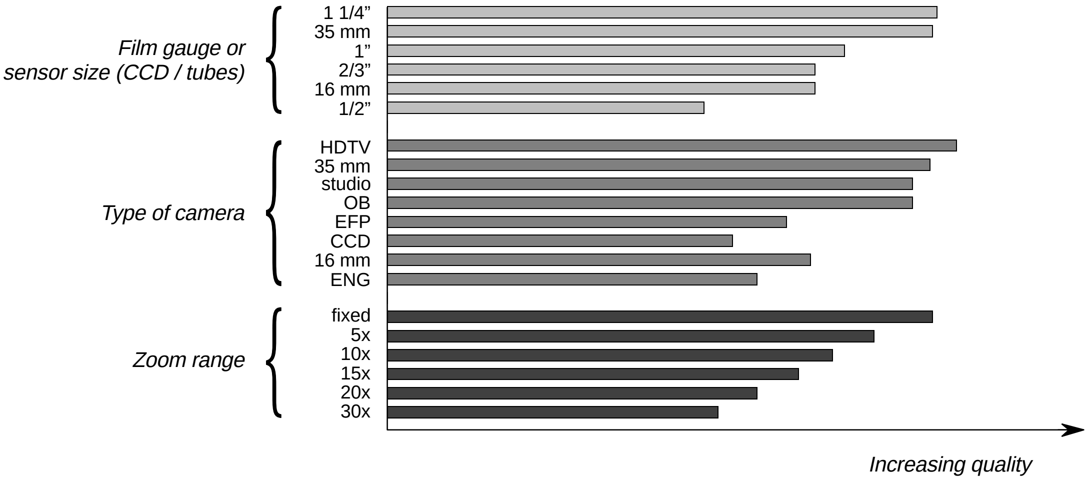
Two examples will illustrate this point:

- A lightweight lens can be expected to be "less good", globally, than a heavy studio lens because it is not possible to include all the optical elements that would be needed to ensure the best possible correction of chromatic aberrations, or because the mechanical assembly may be less rigid, leading to mis–alignment of the optical axes of the elements. (*Note*: the lightweight lens may be globally "less good", but still be perfectly adequate for its intended application, for example when shooting live action in a war zone.)

- A lens with a fixed focal length might be the best choice in a television drama production shot on 35–mm film, where the choice favours optimum picture quality despite the inconvenience of lens changing between shots, or the requirement for matching of spectral transmission characteristics of lenses used in the production.

Fig. 25a and *b* shows, in purely qualitative terms, how a number of physical parameters – image size, camera pick–up tube or sensor size, lens type (fixed focal length or zoom), aperture, angle of view and weight can influence picture quality. The relationships shown in these charts should be regarded more as an indication of trends than any form of direct inter–dependency between picture quality and the individual characteristics.

a) Film gauge or pick–up tube (or CCD sensor) size, type of camera and type of lens.



b) Lens weight, angle of view and nominal aperture.

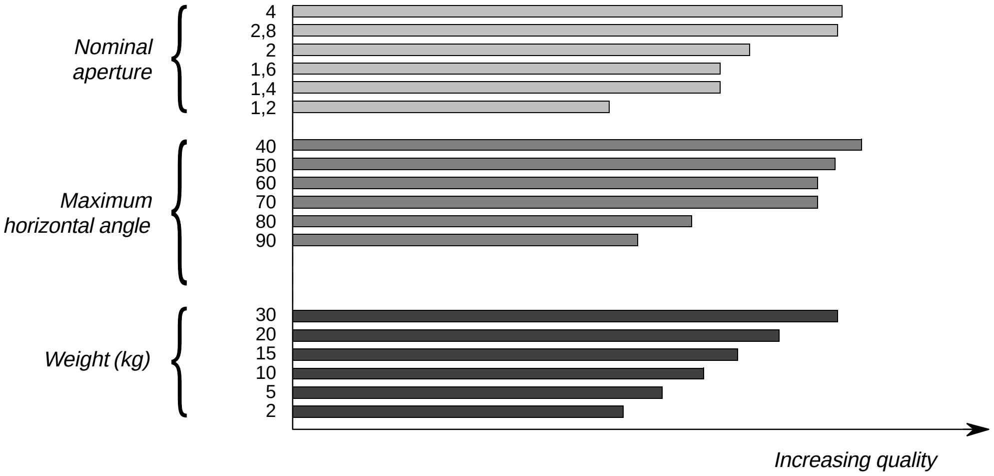


Fig. 25 – Influence of objectively measured parameters on picture quality.

Fig. 26 shows the same parameters as wedges of a pie chart which might be called an "optical quality circle". They are the objective parts of the whole circle, which is completed by two additional wedges. One of these is a subjective indication of the experience needed in order to evaluate picture quality and to make the right decisions when making a choice between the optimum objective parameters. The last wedge, which completes the circle, indicates the amount of electronic error correction needed to give a satisfactory picture.

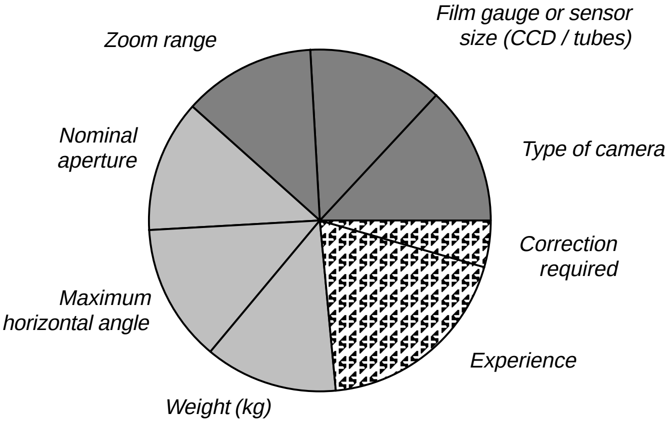


Fig. 26 – Optical quality circle.

3. Statistical analysis and computer processing

In any attempt to reduce the mass of measurement data to manageable proportions, it is important to find solutions which take into account all the data that have been collected, rather than simply discarding some results. This suggests that some form of averaging or integration of the results might be a valid approach. The following sections suggest how this might be done for some of the optical characteristics considered in *Chapter 2*.

Examples of the graphical representation of results of measurements of the modulation transfer function of lenses are shown in *Fig. 5* and *Fig. 6*. A simplified form of presentation, which does not involve the discarding of any of the initial measurement results, is the bar chart shown in *Fig. 27*. The data in this chart represents the integral of the MTF, calculated by integrating the area under the curve between the limits of maximum and minimum focal length.

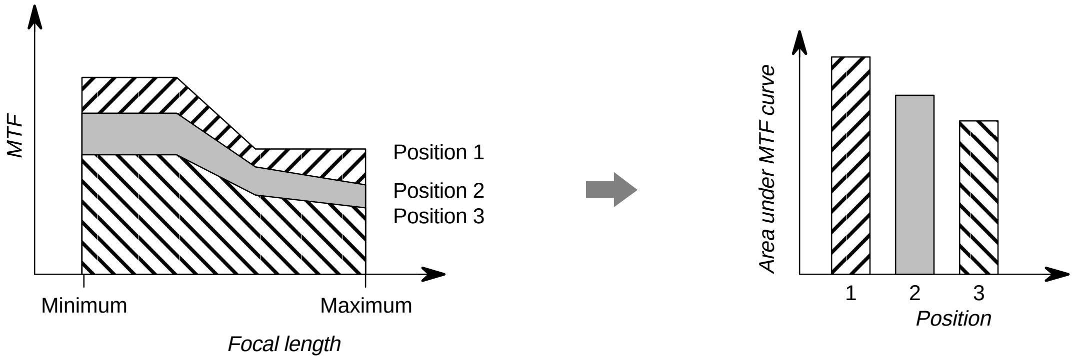


Fig. 27 – Extraction of bar–chart data from a graph of MTF as a function of focal length.

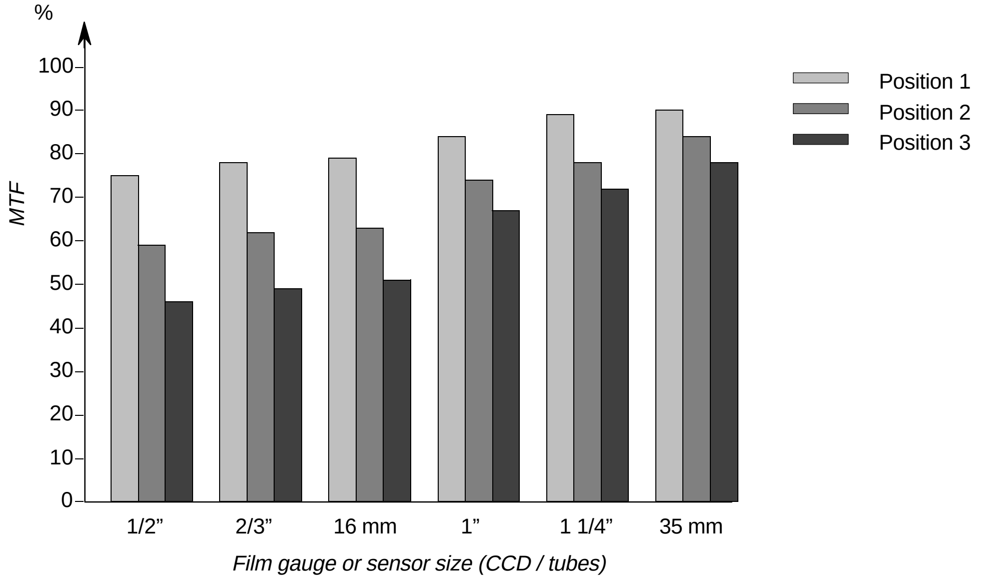


Fig. 28 – Bar–chart representation of typical MTF data.

Fig. 28 shows a complete bar–chart derived from the measurement data for all the typical lenses shown in *Fig. 6.*

After the MTF data have been “reduced” in this way, further analysis is possible. The first group of the bar–chart in *Fig. 29* shows the MTF of a typical 2/3–inch pick–up device, with values of 78%, 62% and 49% for the three field positions 1,2 and 3. The second group of the chart shows the reduced data for lens “X”, calculated as shown in *Fig. 27.* It is easily seen that the MTF of this lens is better than that of the 2/3–inch sensor at all three field positions, so the lens can be used with a camera fitted with that sensor without impairing the MTF of the lens/camera combination. The third group of *Fig. 29* shows the MTF of a typical camera tube (the same for all field positions). If lens “X” is used with a camera fitted with tubes having this MTF characteristic, the resultant modulation at the output of the camera will be 40%, 32%, 26%; this result is shown in the last group of the chart. By this form of analysis, cameramen, vision operators and maintenance personnel can be provided with simple indications of the amount of electronic correction needed for a particular lens/camera combination, without it being necessary for them to understand – or even have access to – the original lens measurement data.

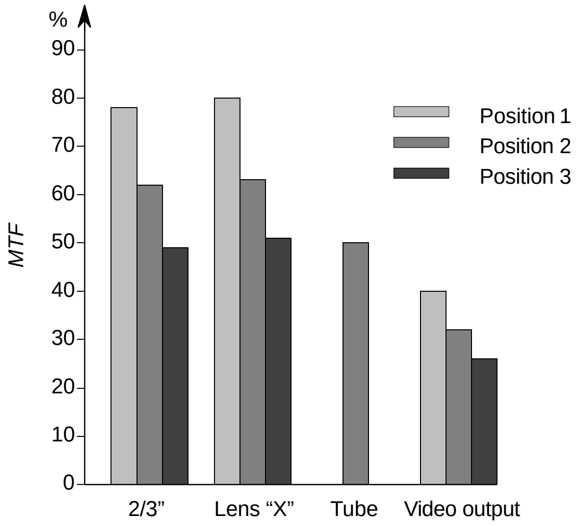


Fig. 29 – Comparison of MTF values of lenses and camera sensors.

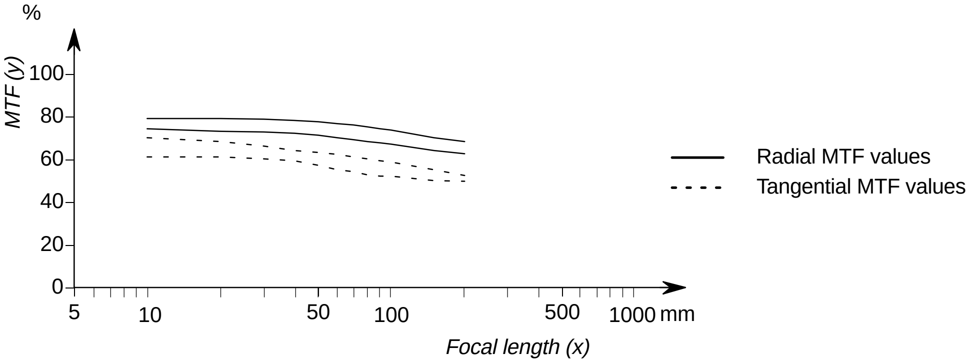
A further stage of data processing can be carried out, to approach more closely the concept of a simple “quality factor”. From the mass of MTF data collected in the basic measurement procedure, the modulation transfer factors for the following conditions are extracted and input to a computer:

- video frequency 5 MHz;
- two apertures (e.g. T/1.6 and T/4);
- radial (R) and tangential (T) modulation transfer factors;
- five focal lengths spread over the full zoom range of the lens;
- field position 2.

Manufacturer:	xyz	**Type**	20 x	**F**	10–200	**T**	1:6	**Nº**	12345	**Date**	03/93	**Page 1b**

Measurement conditions				
Distance : 4.0 m	On axis	position1		
Mount : BVP–360	0.25 d	position 2	x	
Glass block : yes	0.40 d	position 3		
Back focus : maximum	0.50 d	position 4		
Orientation : upright	Radial	—	x	—
Light : 3200 K+G	Tangential		x	----
	Aperture	maximum	x	1:6
	Aperture	4	x	

Quality			
R	1:6	72%	65%
T	1:6	58%	
R	4	83%	76%
T	4	68%	



Focal length	**Tangential MTF**				**Radial MTF**			
	T/4		**T/1.6**		**T/4**		**T/1.6**	
	x	**y**	**x**	**y**	**x**	**y**	**x**	**y**
1	10	70	10	61	10	79	10	74
2	20	68	20	61	20	79	20	73
3	40	64	40	59	40	78	40	72
4	80	60	80	52	80	75	80	68
5	200	52	200	49	200	68	200	62

Fig. 30 – Computer analysis of raw MTF data, and calculation of a “quality factor”.

The computer program produces a conventional graph of MTF as a function of focal length and a table of the selected data. It calculated the area under each curve, and these areas are expressed as a percentage of the area that would be obtained under the MTF curve of a lens whose performance is limited only by diffraction effects (approximateing to an "ideal" lens). The averages of these percentages for the *R* and *T* MTFs respectively lead to just two figures, one representing the quality factor of the lens at T/1.6, the other at T/4. An example of the presentation of results obtained in this form of data processing is shown in *Fig. 30*.

For many purposes, a simple visual representation of the most important characteristics of a lens will be sufficient. As an axample, *Fig. 31* shows a bar chart of modulation transfer factors at 5 MHz, for two apertures and three field positions. This simple chart illustrates the severity of lens aberrations which cause a reduction in the MTF values as the distance from the image centre increases.

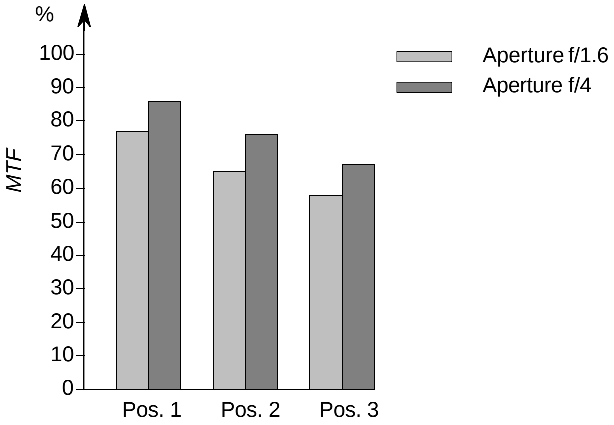


Fig. 31 – Bar chart represention of a critical lens characteristic.

A similar form of processing may be applied to the analysis of other aspects of lens performance. In the case of chromatic aberrations, for example, the areas under the curves of lateral chromatic aberration for the red and blue images are calculated (in arbitrary units) and normalized with reference to the maximum permissible area calculated using the data given in *Section 2.5.4.* of *Chapter 2*. These normalized areas for the red and blue images may be interpreted directly as a "quality factor" for this characteristic.

For zoom tracking errors the areas under the curves (*Fig. 7* for axial errors and *Fig. 8* for lateral errors) can be compared in a bar chart with the areas under curves corresponding to the tolerances indicated in *Sections 2.3.4.* and *2.4.4.* respectively.

Presentation of these different "quality factors" in the form of bar charts then gives a simple visual guide to lens performance (*Fig. 32*).

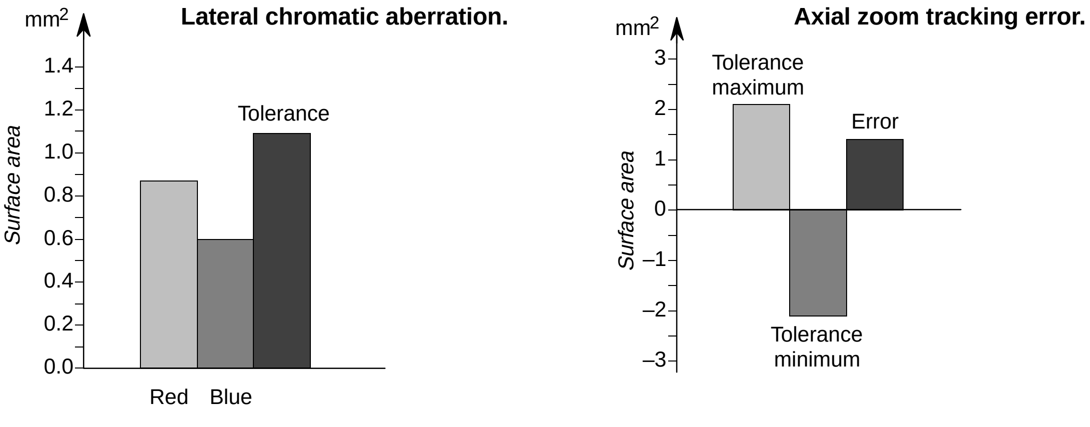


Fig. 32 – Bar chart representation of selected lens characteristics.

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Editeur responsable : G.T. Waters, Ancienne Route 17A, CH–1218 Grand–Saconnex/Genève, Suisse.