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Optics and optical instruments — Quality evaluation of optical systems — Assessing the image quality degradation due to chromatic aberrations

Optique et instrument d'optique — Évaluation de la qualité des systèmes optiques — Estimation de la dégradation de la qualité de l'image due à des aberrations chromatiques

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15795 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 1, *Fundamental standards*.

Annex A of this International Standard is for information only.

Introduction

Aberrations due to the variation of the refractive index with wavelength (dispersion) are usually termed “chromatic aberrations”. Originally, this wording was based on the fact that, in the presence of these aberrations, the image of objects such as points, lines and edges, exhibit coloured fringes in addition to the variation of luminance.

From this point of view, the concept of the point spread function (PSF) and the related optical transfer function (OTF), see ISO 9334, is basically a luminous (or more general radiative) transfer of optical information. There is only one signal regarding wavelength which is the result of the spectral transmission and sensitivity of the transmission chain, even if the latter is not identical to the relative luminous sensitivity of the human eye.

Nowadays, the terms “colour” and, more specifically, “chroma” in the domain of physical science are well defined by colorimetry according to CIE Publication Nr. 15.2 (see reference [1] in the Bibliography) and are restricted to that region of the electromagnetic spectrum, which is accessible to the normal (trichromatic) human observer.

However, when concerned with aberrations due to the dispersive behaviour of electromagnetic waves, it is necessary to take into account that the spectral region of the optical waveband is by far wider than the limits of sensitivity of the human eye. This region may extend from the UV to the medium IR. In such applications, the human visual process is not involved or, if so, only by means of certain translations of the information into the visual waveband.

Nevertheless, the fact of variation of the form and position of the point or line spread function with wavelength or with some spectrally weighted wavebands is still given. To characterize this dispersive behaviour, one has not to deal with colorimetry, but should describe the position and extent of the spread function relative to that of a certain reference wavelength or reference spectral weighting.

In this sense, the present International Standard will not deal with colour sensations, but the term “chromatic aberrations” is used in a purely physical manner to describe the wavelength dependent properties of such aberrations.

The variation of the spread function with wavelength in a given image plane of an optical system may be characterized by a lateral translation and additionally by a variation in form and width.

The lateral translation of a typical coordinate point of the spread function will be called lateral chromatic aberration, whereas the form and extent can be characterized by two numbers derived from a weighting procedure over the spread function (edge width).

The longitudinal chromatic aberration indicates the axial position of the best image plane for a certain wavelength or waveband with respect to a reference plane and for a defined focusing (or image quality) criterion.

Optics and optical instruments — Quality evaluation of optical systems — Assessing the image quality degradation due to chromatic aberrations

1 Scope

This International Standard defines terms relating to chromatic aberrations and indicates the mathematical relationships between those terms.

It also gives general guidance for the measurement of chromatic aberrations and is valid for optical imaging systems which are constructed to be of rotational symmetric imaging geometry. It is also valid for optoelectronic imaging systems.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 9334:1995, *Optics and optical instruments — Optical transfer function — Definitions and mathematical relationships*

ISO 9335:1995, *Optics and optical instruments — Optical transfer function — Principles and procedures of measurement*

ISO 9039:1994, *Optics and optical instruments — Quality evaluation of optical systems — Determination of distortion*

ISO 11421:1997, *Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement*

3 Symbols and units

Symbol	Meaning	Unit	Specified in
λ	Measurement wavelength	nm, µm	4.2.1
λ_r	Reference wavelength	nm, µm	4.3
$W(\lambda)$	Weighted spectral distribution	dimensionless	4.2.2
$W_R(\lambda)$	Weighted spectral reference distribution	dimensionless	4.3
$u(\lambda)$	Local image field coordinate for measurement wavelength	µm	4.5
$u(\lambda_r)$	Local image field coordinate for reference wavelength	µm	4.5
$u(W)$	Local image field coordinate for weighted spectral measurement distribution	µm	4.5

Symbol	Meaning	Unit	Specified in
$u(W_R)$	Local image field coordinate for weighted spectral reference distribution	µm	4.5
$h'(\lambda_r)$, $h'(W_R)$	Image height for reference wavelength or distribution	mm	4.5
$T(\lambda)$	Lateral chromatic aberration	µm	4.6
$T(W)$	Weighted lateral chromatic aberration	µm	4.7
$\mathrm{L}(\lambda)$	Longitudinal chromatic aberration	µm	4.9
$\mathrm{L}(W)$	Weighted longitudinal chromatic aberration	µm	4.9
LE	Left edge width	µm	4.8.2
RE	Right edge width	µm	4.8.2
EW	Edge width	µm	4.8.2
$z'(\lambda)$, $z'(\lambda_r)$	Position of best focus for wavelengths λ and λ_r	mm	4.9
$z'(W)$, $z'(R)$	Position of best focus for spectral weightings $W(\lambda)$ and $W_R(\lambda)$	mm	4.9
ω'_p	Image pupil field angle	degree	3.8 of ISO 9039:1994
ω_p	Object pupil field angle	degree	3.7 of ISO 9039:1994
OTF(r)	One-dimensional optical transfer function	dimensionless	3.11 of ISO 9334:1995
MTF(r)	One-dimensional modulation transfer function	dimensionless	3.9 of ISO 9334:1995
PTF	Phase transfer function	degree, rad	3.10 of ISO 9334:1995
PSF	Point spread function	mm^{-2}	3.5 of ISO 9334:1995
LSF	Line spread function	mm^{-1}	3.13 of ISO 9334:1995
ESF	Edge spread function	dimensionless	3.14 of ISO 9334:1995
ψ	Azimuth	degree	4.21 of ISO 9334:1995
ϕ	Reference angle	degree	4.12 of ISO 9334:1995
ξ	Integration variable	dimensionless	4.5

4 Terms and definitions, principle and mathematical relationships

4.1 General

For the purposes of this International Standard, the terms and definitions given in ISO 9334 and ISO 9335 apply.

4.2 Wavelengths and spectral distributions

For the determination of chromatic aberrations, several wavelengths or spectral distributions shall be given for which the aberrations are to be determined.

4.2.1 Quasi-monochromatic measurement

In this case, the spectral bandwidth of the measurement radiation is small compared to the distance between neighbouring measurement wavelengths.

The measurement wavelength under consideration is the mean wavelength of that quasi-monochromatic radiation for which the chromatic aberrations are to be determined.

4.2.2 Measurement with finite spectral bandwidth

The spectral bandwidth is specified by a spectral weighting function, $W(\lambda)$. For the purpose of analytical calculations, this shall be approximated by spectral area weighting with different discrete wavelengths. The measurements of chromatic aberrations shall always be carried out in the same manner, regardless of whether they are determined for discrete wavelengths or for certain wavebands.

4.3 Reference wavelength and weighted spectral reference distribution

In the case of quasi-monochromatic radiation (see 4.2.1), the reference wavelength, λ_r, is the wavelength to which the determination of the chromatic aberrations is related. In the case of finite spectral bandwidth (see 4.2.2), the reference spectral distribution is the spectral weighting function, $W_R(\lambda)$, to which the determination of the chromatic aberrations is related.

4.4 Measurement plane

The measurement plane is a plane perpendicular to the optical axis in which the measurement is carried out. It may be defined by geometric means, or with the help of a suitably defined focusing criterion, which can be applied by measurement and shall be accessible for analytical calculations.

4.5 Image heights and local image field coordinates

The image heights are defined by means of the line spread function (LSF). Figure 1 shows an example of (measured) line spread functions.

For the definition of line spread function, see 3.13 of ISO 9334:1995. This definition is also valid for weighted spectral distribution, $W(\lambda)$.

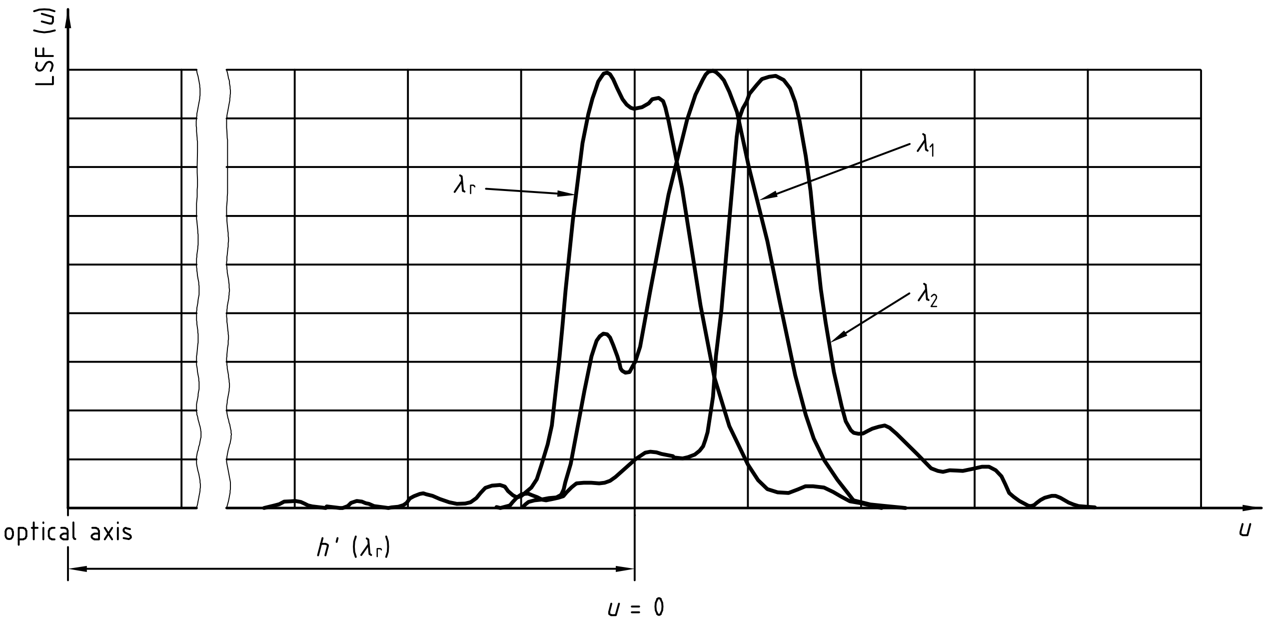


Figure 1 — Examples for quasi-monochromatic line spread functions

The image height, h', is the position within the line spread function where the area fractions of the line spread function are equal.

Thus:

$$\int_{-\infty}^{h'} \mathrm{LSF}\,(\xi)\,\mathrm{d}\xi = \frac{1}{2}\int_{-\infty}^{+\infty} \mathrm{LSF}\,(\xi)\,\mathrm{d}\xi \qquad (1)$$

where ξ is an integration variable.

Local image field coordinates, u, are introduced by choosing the origin $u = 0$ at the reference image height, $h'(\lambda_\mathrm{r})$, for the reference wavelength, λ_r, or $h'(W_\mathrm{R})$ for the weighted spectral reference distribution, $W_\mathrm{R}(\lambda)$.

4.6 Lateral chromatic aberration

The lateral chromatic aberration, $T(\lambda)$, is defined as the radial variation in image height for the wavelength, λ, relative to the image height for the reference wavelength, λ_r. This definition requires a numerical evaluation of the line spread function, as it is also necessary for the determination of the optical transfer function. For given magnification ratio and relative aperture, the lateral chromatic aberration is a function of wavelength and image height.

For finite image distance, the lateral chromatic aberration, $T(\lambda)$, in the measurement plane is given by:

$$T(\lambda) = u(\lambda) - u(\lambda_\mathrm{r}) \qquad (2)$$

where

$u(\lambda_\mathrm{r}) = 0.$

4.7 Weighted lateral chromatic aberration

The weighted lateral chromatic aberration, $T(W)$, is defined as the radial variation in image height, $u(W)$, for the weighted spectral distribution, $W(\lambda)$, relative to the image height, $u(W_\mathrm{R})$, for the weighted spectral reference distribution, $W_\mathrm{R}(\lambda)$. For given magnification ratio and relative aperture, the weighted lateral chromatic aberration in the measurement plane is a function of image height.

For finite image distance:

$$T(W) = u(W) - u(W_\mathrm{R}) \qquad (3)$$

where

$u(W_\mathrm{R}) = 0.$

As in 4.6, this requires a numerical evaluation of the line spread function, here with weighted spectral distribution, $W(\lambda)$.

4.8 Form and extent of the edge spread function (ESF)

4.8.1 General

In addition to the lateral chromatic aberration as a displacement between the median values of the edge spread functions for the reference and measurement wavelength or spectral weighting, one shall judge the degradation in image quality with the help of the form of the line or edge spread function for the different wavelengths or spectral weightings. This will give information in the space domain alternatively to the optical transfer function in the spatial frequency domain. The edge spread function will be used, because, in general, its structure is relatively, simple. See Figure 2.

For the definition of edge spread function, see 3.14 of ISO 9334:1995. This definition is also valid for weighted spectral distribution, $W(\lambda)$.

The edge spread function may be derived from the line spread function by:

$$\mathrm{ESF}\,(u) = \int_{-\infty}^{u} \mathrm{LSF}\,(\xi)\,\mathrm{d}\xi \tag{4}$$

where ξ is an integration variable.

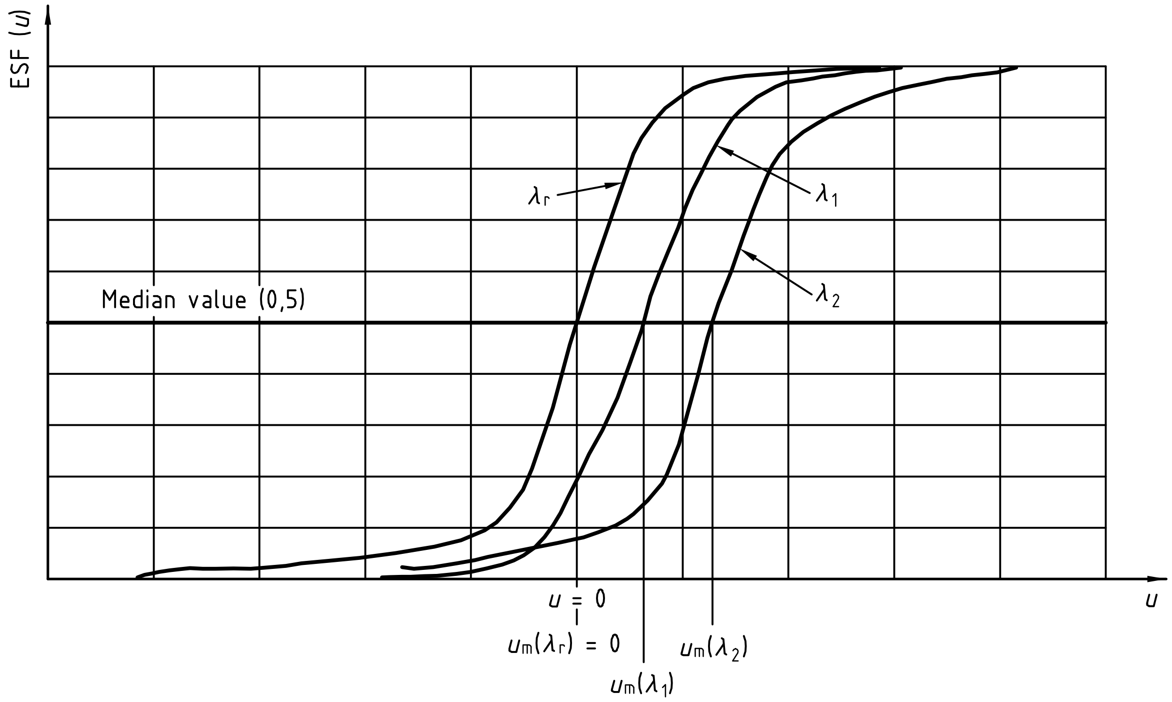


Figure 2 — Examples for quasi-monochromatic edge spread functions

The image height, h', is the median value of the normalized edge spread function.

From the edge spread function, two overall quality criteria in space domain are deduced: left edge width (LE) and right edge width (RE). (See references [2] and [3] in the Bibliography.)

4.8.2 Edge widths

The edge widths shall be defined with the help of the area between real edge spread function ESF(u) and the ideal edge [Heaviside step function H(u)]. The step of the ideal edge lies in the median of the edge spread function (u_m: ESF(u) = ½). With this definition, the two areas between both functions will be minimal. See Figure 3 and reference [3] in the Bibliography.

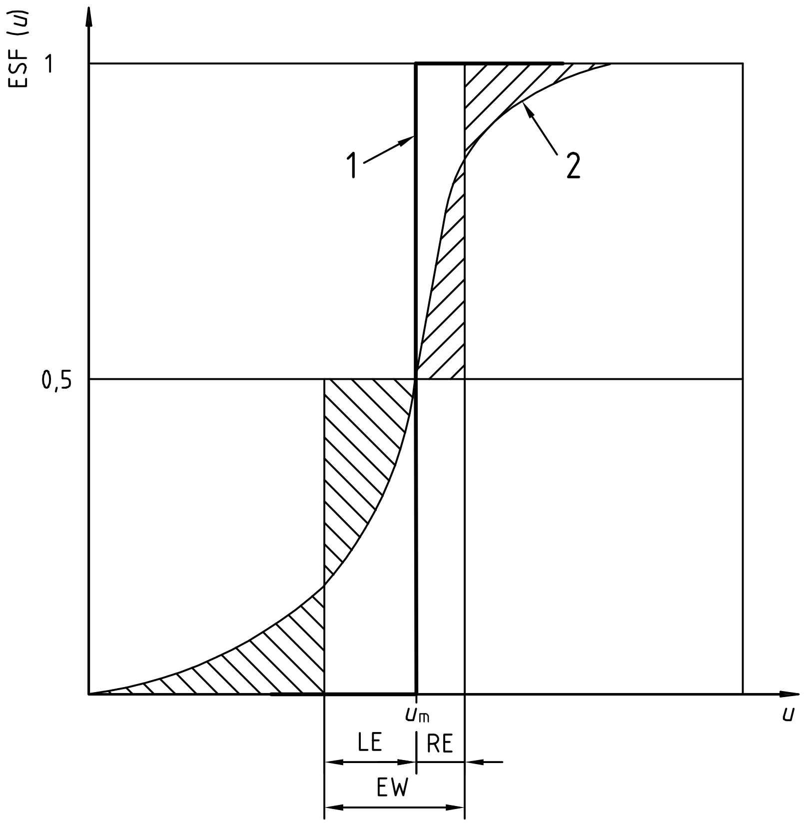
Definitions of the edge widths are as follows:

$$\mathrm{LE} = 2\int_{-\infty}^{u_\mathrm{m}} \mathrm{ESF}\,(u - u_\mathrm{m})\,\mathrm{d}u \tag{5}$$

$$\mathrm{RE} = 2\int_{u_\mathrm{m}}^{+\infty} \left[1 - \mathrm{ESF}\left(u - u_\mathrm{m}\right)\right]\mathrm{d}u \tag{6}$$

$$\mathrm{EW} = \mathrm{RE} + \mathrm{LE} \tag{7}$$

The relation between the edge width (EW) and the line spread function (see references [2] and [3] in the Bibliography) is as follows.



Key

1 Step of the ideal edge [H(u)]

2 Real edge [ESF(u)]

Figure 3 — Definition of the edge widths

Relative to the local coordinate system introduced in 4.8.1, the edge width (EW) is equal to the absolute momentum of first order of the line spread function [LSF(u)]:

$$\text{EW} = \int_{-\infty}^{+\infty} \left| u - u_\text{m} \right| \text{LSF}\,(u)\,\text{d}u \tag{8}$$

The absolute momentum of first order is a minimum for u_m as median position of the edge spread function.

The relation between the edge width (EW) and the optical transfer function [OTF(r)] (see references [2] and [3] in the Bibliography) is as follows.

Relative to the local coordinate system introduced in 4.8.1, the optical transfer function [OTF(r)] shall be given by:

$$\text{OTF}\,(r) = \text{MTF}\,(r)\, e^{i\theta(r)} \tag{9}$$

where

MTF(r) is the modulation transfer function MTF; and

$\theta(r)$ is the phase transfer function PTF

The image shift $V(r)$ is connected to the phase by $V(r) = -\theta(r) / 2\pi r$.

Then the edge width is given by:

$$\mathrm{EW} = \frac{1}{\pi^2} \int_0^\infty \frac{[1 - \mathrm{Re\,OTF}(r)]}{r^2}\, \mathrm{d}r = \frac{1}{\pi^2} \int_0^\infty \frac{[1 - \mathrm{MTF}(r) \cos\theta(r)]}{r^2}\, \mathrm{d}r \qquad (10)$$

where Re OTF(r) is the real part of the OTF.

Thus the edge width will tend to be smaller with higher modulation transfer function (MTF) and lower phase transfer function (PTF) values for the spatial frequency range. This may be represented in terms of decrease of modulation and phase contributions.

$$\mathrm{EW} = \frac{1}{\pi^2} \int_0^\infty \frac{[1 - \mathrm{MTF}(r) + 2\mathrm{MTF}(r) \sin^2 \frac{\theta}{2}]}{r^2}\, \mathrm{d}r \qquad (11)$$

The finite edge width thus results as a contribution of two parts, each one as a sum over all spatial frequencies:

1) MTF(r) = Modulation decrease for spatial frequency, r

2) MTF(r) $\sin^2(\theta/2)$ = Phase disturbance for spatial frequency, r

4.8.3 Chromatic edge widths

Edge width, left and right edge width are functions of the wavelength λ or spectral weighting $W(\lambda)$:

— for quasi-monochromatic radiation: LE(λ), RE(λ), EW(λ)

— for weighted spectral bandwidth W(λ): LE(W), RE(W), EW(W)

The variation of the edge widths (EW, LE, RE) shall be called chromatic edge widths.

4.9 Longitudinal chromatic aberration

General rules for focusing criteria are given in 5.1.5 of ISO 9335:1995. Here the definition of 5.1.5 a) shall be used.

Best focus is the position along the optical axis where the modulation transfer function at a specified spatial frequency, r_0 and for radiation of a specified wavelength or specified weighted wavelength distribution, is a maximum. The position of best focus will be a function of the chosen object conjugate.

Longitudinal chromatic aberration is the longitudinal variation in best focus with wavelength relative to the best focus for the reference wavelength, λ_r.

For a finite image distance, the longitudinal chromatic aberration is given by:

$$L = z'(\lambda) - z'(\lambda_r) \qquad (12)$$

where $z'(\lambda)$ and $z'(\lambda_r)$ are the positions of the best focus (i.e. the image distances) for the wavelengths λ and λ_r respectively.

Weighted longitudinal chromatic aberration is the longitudinal difference between the best focus for a weighted spectral distribution, $W(\lambda)$, and the best focus for the weighted spectral reference distribution, $W_R(\lambda)$.

For a finite image distance, the weighted longitudinal chromatic aberration is given by:

$$\mathrm{L}(W) = z'(W) - z'(R) \quad (13)$$

where $z'(W)$ and $z'(R)$ are the positions of best focus (i.e. the image distances) for the spectral weightings, $W(\lambda)$ and $W_R(\lambda)$, respectively.

5 Classes of applications

The different application-dependent methods of measurement are classified according to ISO 9335 as follows:

— infinite object distance, finite image distance;

— infinite object distance, infinite image distance;

— finite object distance, finite image distance;

— finite object distance, infinite image distance.

However, in this International Standard, only finite image distances are treated in detail.

6 Measurement procedures

6.1 Brief description of the procedures

6.1.1 Measurement of lateral chromatic aberrations and edge width in a fixed measurement plane

The measurement principle relies on the evaluation of the image height of the line or edge spread function for different wavelengths or weighted spectral distributions relative to the corresponding position for the reference wavelength or reference spectral distribution, as well as on the evaluation of the edge widths. The image height is given as the position of equal area fractions for the irradiance in the line spread function.

The position of the reference point will in general exhibit distortion. From this point of view, the lateral chromatic aberration may be thought of as a variation of distortion with wavelength (or weighted spectral distribution). Therefore, the measurement of lateral chromatic aberration is related to the measurement of distortion in the sense that similar methods are used and thus both measurements may be coupled. The difference to the measurement of distortion lies in the fact that the latter is related to the position of the gaussian image point, whereas the lateral chromatic aberration is measured with reference to the spread function at a certain reference wavelength or bandwidth. If the measurement of distortion is carried out with the reference wavelength (or bandwidth), then the lateral chromatic aberrations are connected with the object side positions. The meaning of object side and image side is to be understood from the viewpoint of application. In the case of opposite direction of radiation, care should be taken not to confuse image and object-side quantities, as otherwise the distortion and lateral chromatic aberration would be reversed in sign.

The scanning of the line or edge spread function shall be carried out in the same way as for the measurement of the optical transfer function (ISO 9335).

A single illuminated slit or pinhole whose displacement is measurable serves the purpose of representing object positions of finite distance or, in the case of opposite direction of radiation, image positions of finite distance. Collimators are employed to represent objects at infinite distance.

For the measurement of finite image or object heights, detection devices whose displacement is measurable or scales placed in the measuring plane are employed.

The chromatic aberrations are calculated from the measured values according to the formulas given in clause 4.

6.1.2 Measurement of longitudinal chromatic aberrations

All measurements shall be performed on optical axis (image height $h'_r = 0$) and at a defined aperture. The measurement principle relies on the evaluation of the best focus for different wavelengths or weighted spectral distributions relative to the corresponding position for the reference wavelength or reference spectral distribution.

A set of measurements along the optical axis in sufficiently small steps is carried out and the MTF values at the specified spatial frequency for this set are evaluated. The maximum MTF value will give the position of best focus.

The measurement range shall be chosen such that the maximum MTF value lies within these limits.

6.2 Description of measurement equipment

6.2.1 General requirements

The general requirements on measurement equipment specified in ISO 9335 and ISO 9039 are applied here. In particular, the following points shall be considered:

- matching of the required spectral characteristic;
- all auxiliary optics such as collimators shall be sufficiently well corrected for chromatic aberrations that they do not affect the measured values;
- positioning of the measurement plane for reference and measurement wavelength (or bandwidths respectively) according to the practical application of the optical system.

6.2.2 Infinite object distance, finite image distance

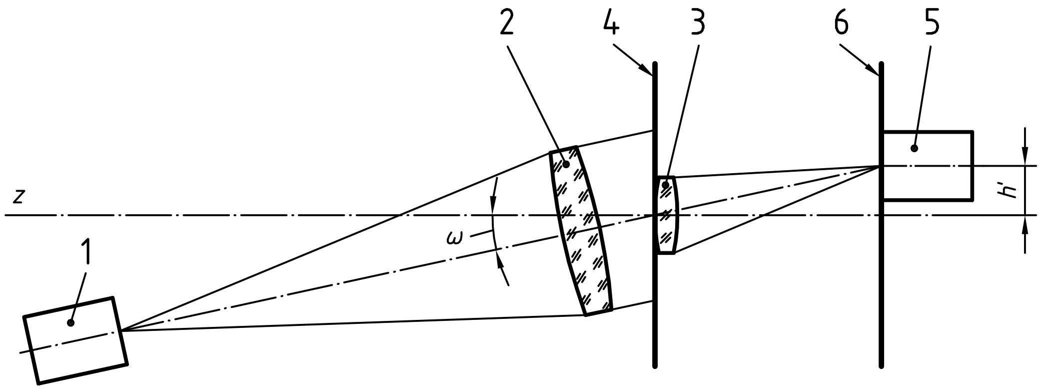
The measurement set-up shall allow the measurement of the image height, h'. If the distortion is not measured simultaneously, there is no need for the determination of the object side field angle. In that case, the object side field angle has to be matched according to the used image height, h'.

The object is represented by an incoherently illuminated narrow slit or pinhole in the focal plane of a collimator. A device whose displacement can be measured is mounted in the image plane of the optical system to be tested in order to detect the image. It shall be possible to rotate the collimator on the one hand the optical system to be tested, with the detection device mounted in its image plane, on the other hand relative to each other in a way that the angle of rotation can be measured. It is of no importance which part is rotated and which part is stationary. The axis of rotation is perpendicular to the plane formed by the image height axis and the optical axis of the collimator and passes approximately through the middle of the entrance pupil of the optical system to be tested.

Prior to starting the measurement, the displacement direction of the image detector shall be aligned parallel to the reference plane of the optical system under test.

The collimator shall be aligned perpendicular to the reference plane. In this way, an object point is realized at the object field angle, $\omega_p = 0$; its image indicates the coordinate origin in the image plane for the test procedure.

As for this basic adjustment, an autocollimating telescope is necessary and it is expedient to design the collimator for use as an autocollimator. The detection device may be a narrow slit with a photoelectric detector mounted behind it. See Figure 4.



Key

1 Test target unit (TTU)
2 Collimator
3 Test specimen
4 Fixture for test specimen
5 Image analyser
6 Image analyser slideway
z Reference axis
ω Object field angle
h' Image height

Figure 4 — Schematic test set-up: Object at infinity (ISO 9335)

6.2.3 Finite object distance, finite image distance

The measurement set-up shall allow the measurement of the image height, u.

If the distortion is not measured simultaneously, the object side image height shall be adjusted according to the used value of u for the reference wavelength, λ_r, or reference waveband, $W_R(\lambda)$.

When the radiation is directed from the object to the image space, an illuminated slit, whose displacement in the object plane can be measured, is mounted in the object plane. The optical system under test is stationary. A device for detecting the image, as described in 6.2.2, is arranged in the image plane of the optical system to be tested. The object plane, the reference plane of the optical system under test and the image plane shall be aligned parallel to each other (Figure 5).

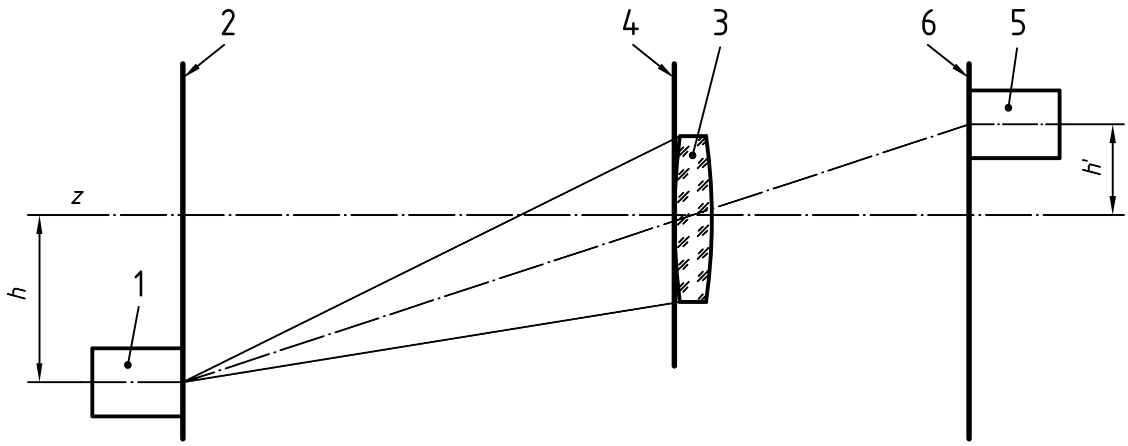
When the radiation is directed from the image to the object space, the measuring slit is arranged in the image plane, whereas the detection device is mounted in the object plane. The image geometry will indicate which direction of radiation is preferable in each individual case.

When the object distance required is too large to be realized in the test laboratory, the method described in 6.2.2 shall be followed in principle. The collimator or the telescope used shall be focused to the object distance required. It may be necessary to refocus the collimator or the telescope with increasing field angle. Care shall be taken to ensure that no axial displacement occurs during refocusing. For this reason, it is advisable to use an alignment telescope.

6.3 Particular measurement conditions

6.3.1 Azimuths, ψ

The measurement should be carried out for tangential and radial azimuth of the test object. Other azimuths may also be selected.



Key

1 Test target unit (TTU)
2 Test target unit slideway
3 Test specimen
4 Fixture for test specimen
5 Image analyser
6 Image analyser slideway
z Reference axis
h, h' Object, image height

Figure 5 — Schematic test set-up: object and image at finite conjugates (ISO 9335)

6.3.2 Orientation, ϕ, of the optical system to be tested

As test specimens are not normally rotationally symmetrical, the chromatic aberrations at a given image height can vary with the reference angle. In this case, measurements should be made at a range of reference angles.

As long as the difference of the extreme values is less than a factor specified for each type of imaging system, the system may be tested for the reference angle, ϕ_0, which has the same chromatic aberration values at $\pm$ 0,7 h'_{max}.

6.3.3 Selection of image heights

It is recommended that the measurement be carried out for the following image heights:

h'_{max} 0,85 h'_{max} 0,7 h'_{max} 0,5 h'_{max} 0,3 h'_{max} 0

The above set of image heights should be used in intercomparisons. However, a different set of image heights may be selected for special applications.

7 Presentation of the results

7.1 Presentation in the form of tables

The presentation of results in the form of tables may be applied in the case of quasi-monochromatic measurement, as well as in the case of finite spectral bandwidth. The rows of the table contain the measurement wavelengths (including the reference wavelength) or the weighted spectral measurement bandwidths (including the weighted reference bandwidth) respectively. The colums of the table contain the values for left edge width, right edge width and the local image height, u. The local image height for the reference wavelength (or weighted spectral reference distribution) has to be taken as zero. The same holds for calculated values. See examples in annex A.

7.2 Graphical presentation

The graphical representation of results is suitable for quasimonochromatic measurements or calculations only. The values for the local image heights, left edge widths LE (starting from the value for the local image height under consideration to the left), right edge width RE (starting from the value for the local image height to the right), are to be plotted in a u - λ diagram. The local image height for the reference wavelength is equal to zero. The corresponding points in the diagram are to be connected by interpolation. Such a graphical representation is valid for a single relative image height according to 6.3. See examples in annex A.

8 Test report

For the presentation of the measured results, where applicable and necessary, the following variable parameters of the measurement or calculation, fixed parameters of the boundary conditions and specifications of the optical system to be tested shall be indicated in the following order.

a) Laboratory or company;

b) Statement whether measured or calculated values;

c) Designation of the optical system tested (e.g. name, manufacturer, serial number);

d) Additional elements;

e) Test procedure according to clause 6;

f) Environmental test conditions;

g) ϕ orientation of the system under test;

h) λ_i measurement wavelengths, λ_i, and reference wavelength, λ_r, or weighted spectral measurement distribution, W_i (λ), and weighted spectral reference distribution, W_R (λ);

i) NA (numerical aperture) or f-number;

j) lateral magnification, m;

k) chosen measurement planes for measurement and reference wavelengths or weighted spectral measurement/reference distribution;

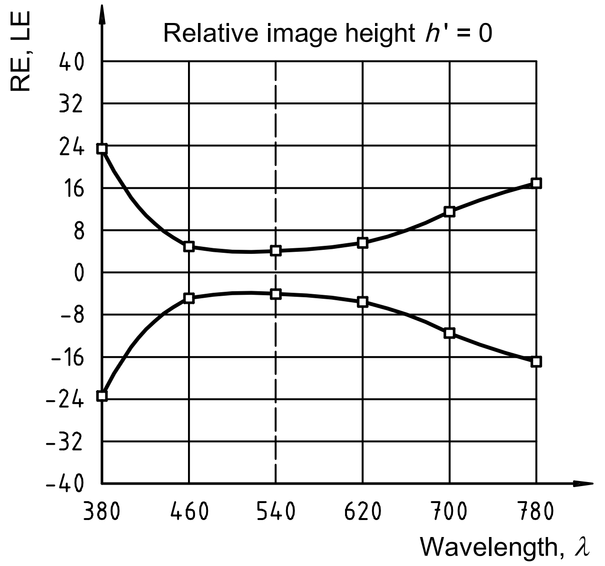
l) statement on the accuracy of the measurement according to ISO 11421.

Annex A
(informative)

Examples of the presentation of results

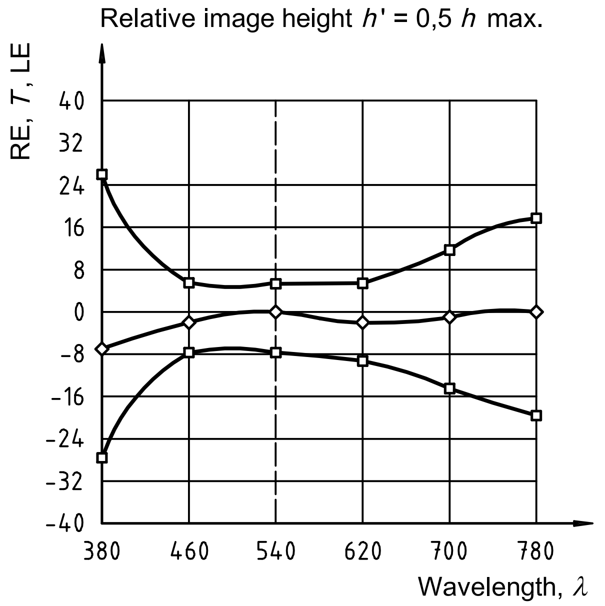
This annex gives an example of the presentation of results in the form of a table, as well as examples of graphical presentation of results (see also clause 7).

Laboratory or company	NN
Measured or calculated values	calculated
Optical system	enlarging lens 1:2,8/50
Spectrum	monochromatic
Reference wavelength	λ_r = 540 nm
Calculated wavelengths	λ = 380, 460, 620, 700, 780 nm
f/number	f/2,8
Magnification	m = – 0,1
Measurement plane	best image plane on optical axis for 20 mm^{-1} and λ_r = 540 nm



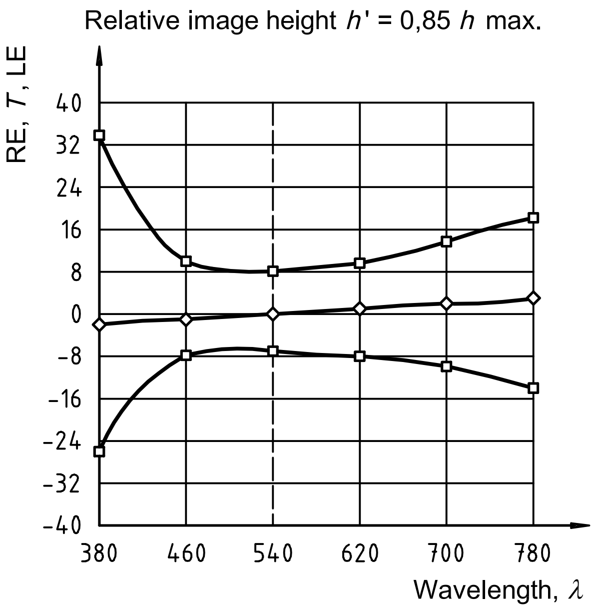
f/no. = 2,8 m = – 0,1; h' = 0

λ	LE/µm	RE/µm	$T(\lambda)$/µm	$L(\lambda)$/µm
380	23,4	– 23,4	0	305
460	4,9	– 4,9	0	7
540	4,1	– 4,1	0	0
620	5,6	– 5,6	0	58
700	11,5	– 11,5	0	135
780	16,9	– 16,9	0	222



f/no. = 2,8 m = – 0,1; h' = 0,5 h max.

λ	LE/µm	RE/µm	$T(\lambda)$/µm
380	26,0	– 27,6	– 7,5
460	5,5	– 7,7	– 2,0
540	5,3	– 7,7	0
620	5,4	– 9,3	– 2,0
700	11,7	– 14,5	0
780	17,7	– 19,6	0



f/no. = 2,8 m = – 0,1; h' = 0,85 h max.

λ	LE/µm	RE/µm	$T(\lambda)$/µm
380	33,8	– 26,0	– 2,0
460	10,0	– 7,8	0
540	8,1	– 7,0	0
620	9,6	– 8,0	– 1,0
700	13,7	– 9,9	– 2,0
780	18,2	– 14,0	– 3,0

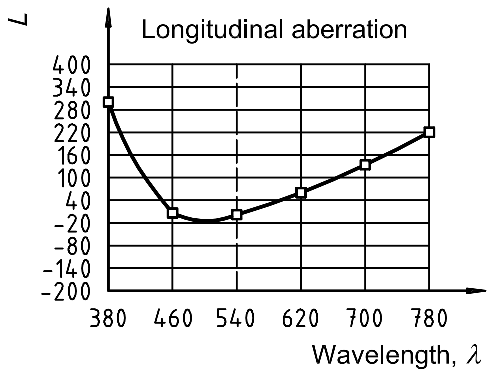


Figure A.1 — Example of calculated chromatic aberrations

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