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Optics and photonics — Optical transfer function — Principles and procedures of measurement

Optique et photonique — Fonction de transfert optique — Principes et procédures de mesure

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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 2.

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 document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 9335 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental standards*.

This second edition cancels and replaces the first edition (ISO 9335:1995), of which it constitutes a minor revision. It also incorporates the Technical Corrigendum ISO 9335:1995/Cor.1:2005.

Introduction

The optical transfer function is an important aid to objective evaluation of the image-forming capability of optical, electro-optical and photographic systems.

In order that optical transfer function measurements achieved using different measuring principles or obtained from measuring instruments in different laboratories can be compared, it is necessary to ensure equivalence of measurement parameters such as focus setting and spatial frequency range. For this reason, an agreed terminology has been defined in order for the measurement parameters used in this International Standard to be understood by all users. This International Standard gives guidance for the construction and operation of equipment for optical transfer function measurement.

The specifications in this International Standard form the basic requirements of measurement instrumentation and procedures for guaranteeing a defined accuracy of measurement of the optical transfer function.

Optics and photonics — Optical transfer function — Principles and procedures of measurement

1 Scope

This International Standard gives general guidance for the construction and use of equipment for measurement of the optical transfer function (OTF) of imaging systems.

This International Standard specifies important factors that can influence the measurement of the OTF, and gives general rules for equipment performance requirements and environmental controls. It specifies important precautions that should be taken to ensure accurate measurements and correction factors to be applied to the collected data.

The OTF measuring equipment described in this International Standard is restricted to that which analyses the radiation distribution in the image plane of the optical imaging system under test. Interferometer-based instruments are outside the scope of this International Standard.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 9334, *Optics and photonics — Optical transfer function — Definitions and mathematical relationships*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 9334 apply.

4 Measuring equipment and environment

4.1 General aspects

4.1.1 Measuring conditions

Any measured OTF depends on the imaging state (I-state) of the imaging system. Thus, before making measurements, those parameters which form the I-state of the system shall be identified and the degree to which the I-state depends on those parameters determined. The complete set of parameters that form the I-state shall be set to fixed values. The fixed values represent a particular I-state and are called the measuring conditions.

4.1.2 Accuracy of measurement

The measuring equipment, and the environment in which it is used, shall allow the prescribed measuring conditions to be set and maintained to a precision which is consistent with the required accuracy of measurement (see ISO 11421, which describes the various parameters which have an impact on the accuracy of measurement). The accuracy of an OTF measurement may be considered as the combination of measurement uncertainties arising from the many separate parameters in the I-state. When a required accuracy of OTF measurement is stated, it shall be apportioned among the known contributing parameters such that a tolerance can be set for each parameter of the I-state. Thus, an overall requirement to an accuracy of measurement of ±0,05 of the modulation transfer function (MTF) might require, among other factors, a temperature stability of the measuring equipment of ±1 °C and focal plane setting to ±5 μm. The discussion of instrumental and environmental settings in the following subclauses relates to tolerances apportioned from the required OTF measurement accuracy in this manner.

4.2 Environment

4.2.1 General

The ambient conditions of the OTF equipment shall be kept sufficiently free from influences that can lead to climatic, mechanical or electromagnetic disturbances. The measuring equipment and the atmosphere in the measuring room shall be kept free from dust, moisture and smoke. All optical surfaces shall be protected from the incidence of scratches and finger prints.

4.2.2 Temperature and humidity control

The temperature shall be kept constant within a stated tolerance and at a suitable value. Humidity shall also be kept within acceptable limits. Both temperature and humidity shall be recorded. Air turbulence and stratification may affect the measurement and shall be minimized through the use of shielding.

4.2.3 Vibration

Vibration shall be kept to a minimum and the use of basement space is recommended if vibration, caused for example by machinery, cannot otherwise be avoided. The degree of vibration isolation for a given measuring accuracy depends on the characteristics of the vibration, the measuring method, and the spatial frequency range. If the method consists of measuring the line spread function, a suitable tolerance might be that the movement of the image and the analyser caused by vibrations should not exceed, for example, 1/20 of the width at half the maximum intensity of the test slit image.

4.2.4 Electromagnetic disturbances

For some systems, it can be necessary to monitor power supply vibrations and keep these to a tolerable minimum. The influence of external electromagnetic fields and the level of ambient light shall be reduced until they do not affect the measured OTF significantly.

4.3 Measuring equipment

4.3.1 Optical mounts

The basis of any measuring equipment shall be a sturdy optical bench or plate, to which mountings for the test target unit, test specimen, image analyser and other auxiliary units can be attached and brought into position, with respect to each other, to the required accuracy.

Depending on the imaging systems to be tested, different requirements can arise regarding the linearity of adjustments and/or the parallelism of equipment slideways. Deviations from ideal linearity and parallelism requirements shall not cause a greater change of the measured MTF than 1/3 of the permitted or specified measurement accuracy.

4.3.2 Defocusing tolerance

For photographic lenses, the defocusing effects caused by bench misalignment result in errors in the measured MTF which increase with rising spatial frequency or with decreasing *f*-number and reduced wavefront aberration. Table 1 gives the defocusing tolerances of a diffraction-limited lens with circular pupil and incoherent illumination that leads to a ±0,05 MTF change. The wavelength of the light is assumed to be 500 nm.

Table 1 — Defocusing tolerances

Dimensions in micrometres

f-number	Defocusing tolerance for spatial frequency mm^{-1}					
	1	5	10	20	50	100
1	45	9	4,5	2,3	1,0	0,5
1,4	62	12,5	6,3	3,2	1,4	0,8
2	89	18	9	4,7	2,0	1,1
4	180	36,5	18,8	9,8	4,6	3
8	360	74	39	21,5	12	12,2
16	720	157	86	54	49	468

NOTE For a change of 0,10 in MTF, defocusing tolerances are twice those shown in this table.

4.3.3 Provision of measuring scales

The measuring equipment shall provide adequate means for determining the positions of test target, system or device under test (test specimen), image analyser and auxiliary systems. These include scales, spindles and dial gauges. Furthermore, means shall be provided to monitor, set or determine all other parameters that form the I-state of the specimen.

4.4 System components

4.4.1 General

The following subclauses give details concerning the measuring arrangement and its basic elements including the test target unit, test specimen, image analyser and auxiliary imaging systems.

4.4.2 Optical benches

4.4.2.1 General

Several arrangements of the measuring equipment are possible, but those in 4.4.2.2 to 4.4.2.5 are recommended.

4.4.2.2 Object and image at finite conjugates

For tests in which object and image are at finite distances from the test specimen, the configurations shown in Figure 1 or 2 shall be used. In these arrangements, two of the three basic units (test specimen, test target unit and image analyser) are moved along slideways parallel to one another and perpendicular to the reference axis. Usually, the test specimen is fixed and the other two units moved as shown in Figures 1 and 2.

When electro-optical components such as image intensifiers are to be tested, auxiliary imaging systems are used to produce an image of the test pattern at the input of the test specimen. The image at the output of the test specimen is then relayed to the image analyser. The corresponding arrangement is shown in Figure 2.

4.4.2.3 Nominal infinite object conjugate

For tests in which the object conjugate is infinite (i.e. the test target is at the principal focus of a collimator), arrangements similar to that shown in Figure 3 shall be used. When off-axis measurements are to be made, the collimator may be rotated by an angle ω about an axis passing through the entrance pupil of the test specimen and perpendicular to the reference axis (see Figure 3).

Alternatively, the collimator may be fixed and the test specimen and image analyser rotated together about the entrance pupil. In this case, the mounting fixture for the test specimen and the image analyser slideway are both rigidly fixed to a rotating baseplate (this arrangement is consequently often referred to as the “rotary table” type).

4.4.2.4 Nominal infinite image conjugate

The same arrangement as described in 4.4.2.3 (see Figure 3) shall be used, with the image analyser and test target unit interchanged.

4.4.2.5 Object and image at nominal infinite conjugates

For systems which are tested with both the object and image at infinite conjugates, arrangements similar to those shown in Figure 4 shall be used. When off-axis measurements are to be made, the object side collimator with the test target unit should be rotated by an angle ω about an axis passing through the entrance pupil and perpendicular to the reference axis of the test specimen. The image side decollimator, together with the image analyser, shall be rotated by an angle ω' about an axis passing through the exit pupil and perpendicular to the reference axis and shall be refocused according to the test criteria.

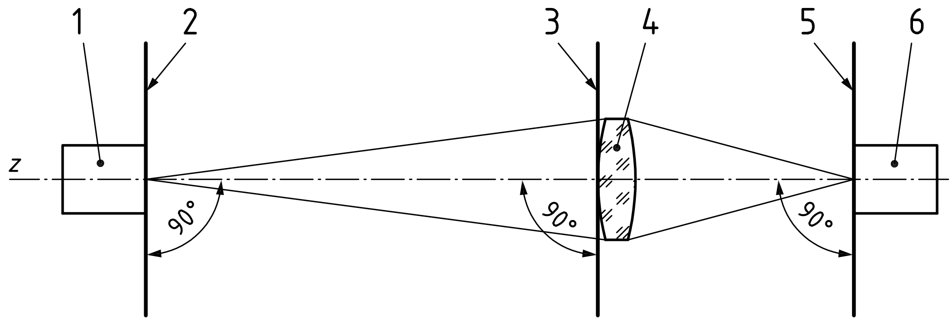
4.4.3 Test target unit

4.4.3.1 General

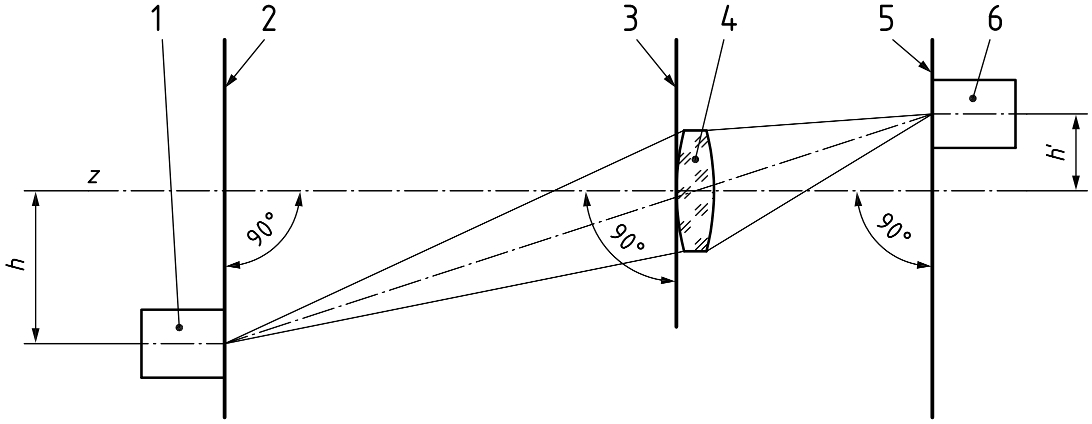
The test target unit shall consist of a source of radiation and a test target.

4.4.3.2 Test target

Depending on the characteristics of the test specimen, several different types of test target may be used. Circular apertures, slits, edges, gratings and self-luminous test targets such as incandescent wires are commonly used. The spatial frequency spectrum of the test target used for the OTF measurement shall be known with an accuracy that is determined by the required measuring accuracy. The actual frequency spectrum of the test target usually differs from its ideal (geometrically predicted) spectrum. If the actual spectrum cannot be measured, precautions shall be taken to ensure that the target is as close as necessary to the specified geometry.



a) On-axis

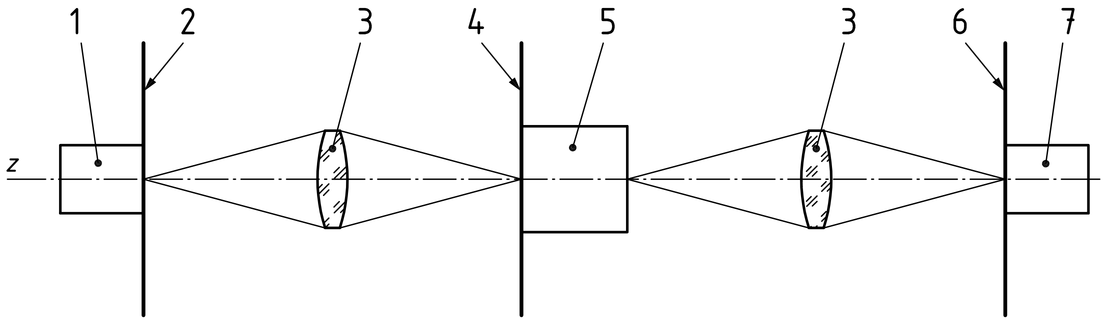


b) Off-axis

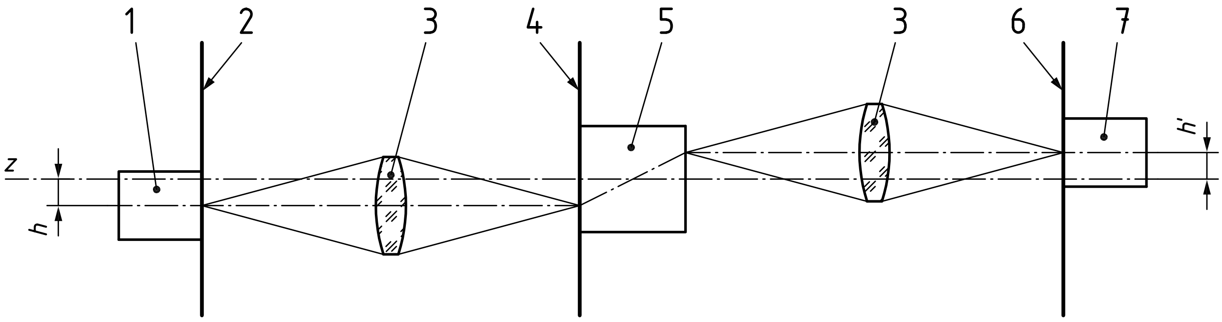
Key

1 test target unit (TTU)
2 TTU slideway
3 fixture for test specimen
4 test specimen
5 image analyser slideway
6 image analyser
z reference axis
h, h′ object, image heights

Figure 1 — Schematic test setup: object and image at finite conjugates



a) On-axis

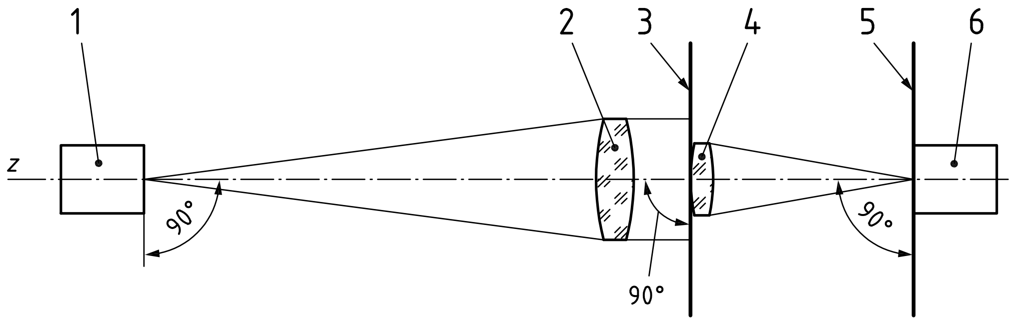


b) Off-axis

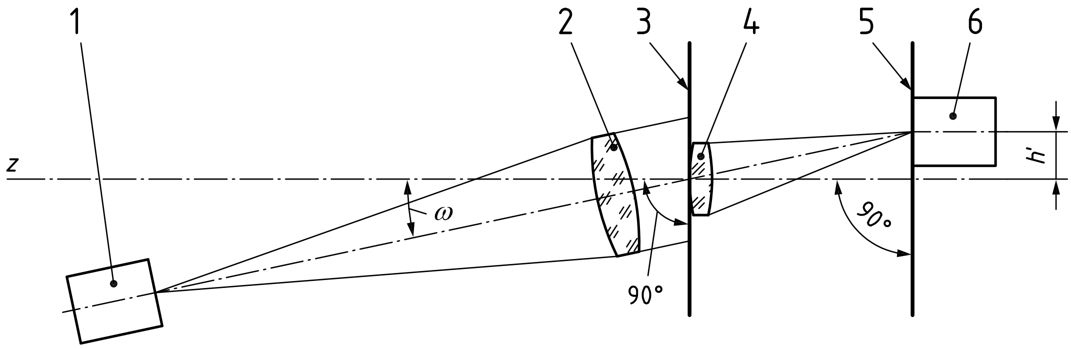
Key

1 TTU
2 TTU slideway
3 relay lenses
4 fixture for test specimen
5 test specimen
6 image analyser slideway
7 image analyser
z reference axis
h, h′ object, image heights

Figure 2 — Schematic setup for image intensifiers



a) On-axis

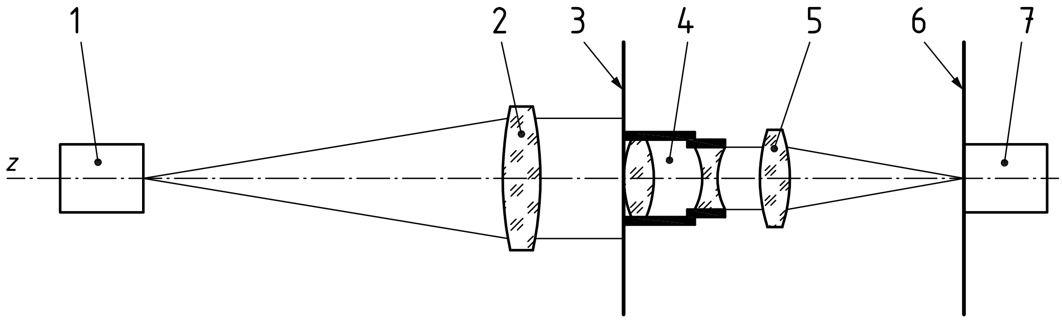


b) Off-axis

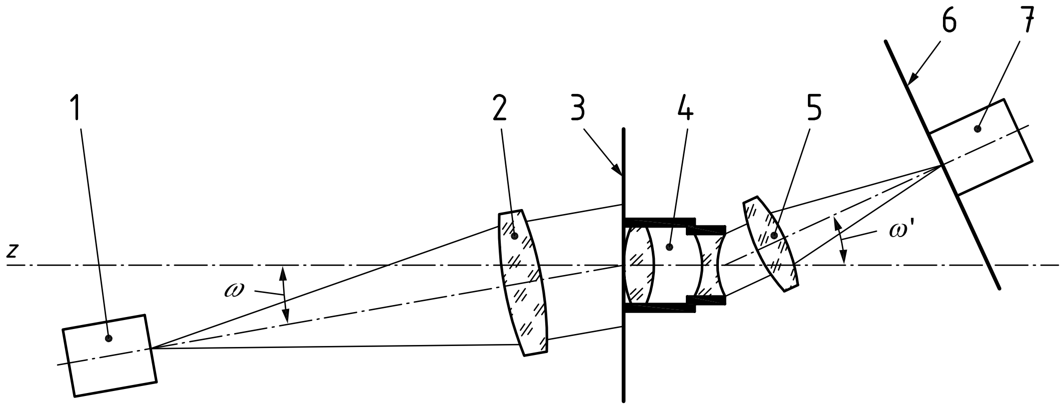
Key

1 TTU
2 collimator
3 fixture for test specimen
4 test specimen
5 image analyser slideway
6 image analyser
z reference axis
ω object field angle
h' image height

Figure 3 — Schematic test setup: object at infinity



a) On-axis



b) Off-axis

Key

1	TTU
2	collimator
3	fixture for test specimen
4	test specimen
5	image-side decollimator
6	image analyser slideway
7	image analyser
z	reference axis
ω, ω'	object and image field angles

Figure 4 — Schematic test setup: object and image at infinity

EXAMPLE In the case of a slit, its width should remain constant over the effective length. A typical tolerance on the parallelism of the edges of a slit is 2 % of its average width and the edge roughness should not exceed 10 % of this average width. As well as specifying the tolerances of the slit itself, it is also necessary to specify the transmittance of the surroundings to the slit. Depending on the required measurement accuracy, the ratio of the total radiant flux from the open slit area to the total radiant flux from the dark surrounds should not be less than a specified factor. A factor of 1 000 is usually sufficient for most optical systems.

In order to be able to perform OTF measurements in different azimuths, it shall be possible to alter the direction of non-rotationally symmetric test targets. Some imaging systems rotate the image of the test targets, therefore a fine adjustment can be necessary in order to turn the image of the test target or the analysing element to the proper azimuth for analysis.

The extent of the test target shall be controllable in order that the condition for an isoplanatic region can be checked and satisfied.

4.4.3.3 Irradiation

The spectral emission and the overall spatial radiation distribution of the source shall be kept constant and free from ripple during the period of measurement.

The test target shall be irradiated or radiate uniformly in the direction of the scan.

Filters may be used to obtain the desired spectral distribution and to prevent the test target being damaged by overheating.

Radiating screens, diffusers, limiting apertures or other components can be used to obtain the required angular distribution of the radiation.

The radiation from the test target shall be sufficiently incoherent. Adequate incoherence is in most cases obtained when the numerical aperture of the condenser, on the test target side, is twice as large as that of the test specimen. In addition, incoherence may also be achieved by inserting a diffuser between the source and the test target in close proximity to the target. If the test target is self-luminous (e.g. an incandescent wire), the incoherence condition will always be fulfilled.

One test to determine whether the irradiation of the target is sufficiently incoherent is to insert a phase plate between the light source and the test target in close proximity to the target and verify that it does not alter the measured MTF or PTF.

4.4.4 Mounting of the test specimen

The test specimen shall be rotatable to the test target so that it can be checked at different reference angles.

The alignment of the test specimen with the mounting fixture shall also be checked, especially where adaptors are used between the mounting face of the specimen and the face of the fixture.

4.4.5 Image evaluation system

The image evaluation system comprises the image analyser and any associated signal processing apparatus used to evaluate the OTF. Two basic forms of image evaluation system are in common use. The first of these performs a direct analogue Fourier transformation by scanning the irradiance distribution in the image of a slit test pattern with a variable spatial frequency analysing element. The second method measures the irradiance distribution in the image of a slit test pattern and computes the image plane spatial frequency spectrum which, suitably normalized, is the OTF. It is important that the radiation detector in the image analyser and the signal processing circuits operate within their linear ranges. After the application of corrections to take account of the spatial frequency spectrum of the test target and other factors (see Clause 5), the result is the OTF or the MTF of the test specimen. The precision of the frequency analysis shall be sufficient to remain within the required overall measurement accuracy.

The analysing element is usually a slit, an edge, or a grating whose dimensions and orientation are adjustable in accordance with the image to be analysed.

Scanning is effected by relative motion of the analysing element with respect to the image. Provided the temporal characteristics and non-isoplanatism of the test specimen cause no measuring inaccuracies and the local scaling factor is known, either the test target or the analysing element may be the moving part.

The length of scan shall be sufficient to extract from the image all the information necessary to compute the OTF with the required accuracy (see 5.3.5.)

The spectral and angular sensitivity of the radiation detector shall be known and specified in the measuring conditions and the analyser shall not be the limiting factor in setting the output aperture of the test specimen.

Precautions shall be taken to ensure that inhomogeneities, non-linearity and instability of the detector do not influence the measurement accuracy significantly. For example, power supplies shall be stabilized and the effects of local variations in the sensitivity of the photocathode surface are eliminated by the use of diffusers. The influence of strong local electromagnetic radiations should also be considered.

The radiation transmitted by the dark surround of the analysing element and impinging on the detector shall be kept to a minimum. Depending on the measuring accuracy required, the energy transmitted by the open area shall exceed the energy transmitted by the dark surround by a factor of at least ×1 000 within the specified spectral range.

If the spatial frequency spectrum of the image is analysed with an analogue electric filter, the bandwidth of the filter shall be narrow enough to resolve the spatial frequency spectrum of the OTF. If the spectrum analysis is carried out using multiple filters, the filter characteristics such as the gain and the phase within the passband shall be equalized or corrected for each filter.

4.4.6 Auxiliary imaging systems

If an auxiliary imaging system, such as a collimator used for the simulation of long object distances or as a part of the image analyser, is included with the test specimen, then its wavefront aberration, within the effective spectral range, shall be small enough to be negligible in comparison with that expected for the test specimen (for example by a factor of 1/10). The collimator shall not limit the entrance or exit apertures of the test specimen.

If a microscope objective lens is employed for the enlargement of the image of the test target, care shall be taken that its numerical aperture is sufficiently large to avoid vignetting for both on-axis and off-axis measurements, and that its aberration shall be small compared with that of the test specimen.

If incoherently coupled auxiliary imaging systems are used, for example when testing image intensifier tubes, their OTF shall be known so that their influence on the measured OTF may be corrected using the product rule [see Equation (1)]. If, under application conditions, auxiliary optical elements, such as windows or graticules, are present between the object field and the image field of the test specimen, these elements shall be included or simulated in the measuring instrument.

Care shall be taken to ensure that the transmittances of all auxiliary imaging components are compatible with other required spectral characteristics.

5 Measurement procedures

5.1 General

Prior to the actual measurement, the measuring conditions that specify a particular I-state of the test specimen shall be set to their prescribed values. The precision with which those settings are made shall be noted and their influence on the overall measurement accuracy assessed.

After the measurement, corrections might be required to take into account the measuring principle and measuring equipment employed. The application of such corrections is described in Clause 6.

5.2 Setting the measuring conditions

5.2.1 General

In 5.2.2 to 5.2.6, general remarks are made on the setting of the measuring conditions and their influence on measurement accuracy. Only those measuring conditions that are similar for all imaging systems are considered. Special requirements for particular systems are given in ISO 9336 (all parts).

5.2.2 Environmental conditions

Environmental parameters such as temperature, humidity and air pressure are part of the measuring conditions. It is necessary to ensure that they are within acceptable limits before commencing measurements.

The test specimen shall be free of dust and fingerprints.

5.2.3 Spectral characteristics

The spectral distribution of the test target radiation and the spectral responsivity of the image analyser shall be set according to the required measuring conditions, for example by the inclusion of appropriate filters.

If the test specimen does not convert the input radiation into radiation with a completely unrelated spectral distribution (as is done by electro-optical imaging systems), it is sufficient to specify the overall characteristics of the combination of source, detector, filter and other auxiliary components used.

5.2.4 Angular distribution and aperture considerations

The angular distribution of the radiation impinging on the test specimen shall be shaped to the required form by the use of suitable sources and/or diffusers. Care shall be taken that the radiation is bounded only by the entrance aperture of the test specimen. Furthermore, the angular response of the image analyser shall satisfy the specified measuring conditions.

5.2.5 Image scale and magnification

Usually, the setting of the image scale and the focusing are closely related to each other.

If a lens or a mirror system is to be tested at finite conjugates, either the image scale, the object-image distance or the back vertex focal distance shall be specified. If the magnification and the position of the nodal planes are specified, the corresponding object and image position can be computed using Newton’s lens equation.

If a lens or mirror system has to be tested at infinite conjugates, the measuring configuration shall be set in accordance with 4.4.2.

If the test specimen is an electro-optical imaging component (e.g. an image intensifier), the image scale is determined by appropriate methods. The image scales of any auxiliary optical systems included in the measurement system shall be adjusted independently of each other. If the test specimen is an imaging system consisting of an assembly of several optical and/or electro-optical components, the image scale of each individual component can require separate setting.

NOTE When using periodic test targets, the spatial frequency local scaling factor may be determined from an accurate measurement of their periodicity in the image plane.

5.2.6 Focusing

The focusing criterion constitutes part of the measuring conditions and is often used to establish the datum plane. Focusing shall not alter the image scale by an amount greater than that allowed by the required measuring accuracy.

EXAMPLE The focusing criterion may be one of the following.

a) The test specimen is focused on axis to the maximum MTF value at a given spatial frequency, r_0. In practice, this criterion can be implemented by taking the datum plane as being midway between the two planes where the MTF has fallen to a prescribed percentage of the maximum value of MTF (r_0).

b) For a test specimen with astigmatism and field curvature, an optimal measurement surface can be specified. This should be determined by taking preliminary MTF measurements at different planes, positions on the field and with different test target orientations and then making an appropriate average using specified rules.

c) Optimization using other sharpness characteristics, such as the LSF peak intensity, edge gradient, spatial bandwidth, etc.

5.3 Additional considerations of measurement

5.3.1 General

The OTF measurement is influenced by a number of additional parameters. Therefore, it is essential that the setting of these parameters be correct. The most important parameters are those given in 5.3.2 to 5.3.9.

5.3.2 Linear range of test specimen

The test specimen shall be operated in its linear range. This can be checked for many systems by varying the input irradiance by a factor of, for example, 5. The measured OTF values, which are automatically normalized, should then not change by more than the tolerance allowed by the required measuring accuracy.

If an imaging system behaves in a non-linear manner, departures from these requirements are permissible; in this case, special procedures are indicated in ISO 9336 (all parts).

If the linear range is bounded at its lower end by a non-zero level, which is the case for video systems, the OTF should be measured using image signal differences. In such cases, it is possible that the image signal differences contain positive as well as negative signals, an example of which is AC coupling effects in video systems.

The effect of such phenomena is that the modulus of the OTF, as evaluated from the measured spread function, does not have its maximum at zero spatial frequency. In order to circumvent a possible arbitrariness in the normalization procedure, the convention shall be adopted whereby the OTF is normalized to unity at the frequency closest (or equal) to zero spatial frequency, where the modulus of the Fourier transform of the measured spread function reaches a minimum value. In this way, the closest agreement with the conventional case is reached.

5.3.3 Isoplanatic region

The extent of the test target used should not exceed the size of the isoplanatic region of the test specimen. This requirement may be tested by measuring the OTF at full and half test pattern size. The requirement may be deemed to have been met if the two OTFs are of equal value within the tolerance derived from the required measurement accuracy.

5.3.4 Fixed pattern noise

The image plane of the test target may contain fixed pattern noise as given, for example, by the grain size of phosphor screens or diffusing screens. The test target and the analysing element should be large enough to avoid any effects of fixed pattern noise on the measurement. If, in the presence of fixed pattern noise, the test target is reduced in size by half without affecting the measured OTF, then the influence of fixed pattern noise is not significant.

5.3.5 Analysed area

The area of the image plane to be analysed depends on the imaging quality of the test specimen and on the required measuring accuracy. If the analysed area is too small, truncation errors will result since the point spread function is assumed to have zero value outside the analysed area. On the other hand, if the analysed area is too large, other errors can be introduced (e.g. from background illumination).

NOTE When the edge spread function (ESF) is available, it is possible to check if the analysed area is large enough since the ESF should start and finish with a straight horizontal line.

5.3.6 Background radiation

The background is that part of the output radiation or signal which is not caused by the object under consideration and can be caused by ambient light or by dark current in electro-optical imaging systems. Background radiation causes a rapid drop in the measured MTF as the spatial frequency increases from its nominally zero value.

The measuring system shall always be shielded as much as possible from ambient light. Background radiation produces a dark current which contributes to the measured signal as an additive background signal. On varying the irradiance of the test pattern, the OTF close to zero spatial frequency should remain unaltered. If the background signal affects the measured signal by more than that allowed by the measuring accuracy, it shall be subtracted before performing the Fourier transform. The elimination of the background can also be accomplished if the complex spectrum of the measured signal, including the background signal, and the complex spectrum of the background signal alone are available. In that case, the complex background spectrum shall be subtracted from the complex measured spectrum.

5.3.7 Veiling glare

In general, an exact separation of the influences on the OTF caused by aberrations and veiling glare is impossible.

Any remaining rapid drop in the measured MTF as the spatial frequency increases from its nominal zero value, after correcting for the background radiation, can be an indication of veiling glare (see 6.1.).

5.3.8 Parallelism of image and analysing element

If the test pattern is in the form of bar targets or other non-rotationally-symmetric object structures, the image of the test pattern and the analysis element shall be set parallel or in a prescribed orientation with respect to one another.

This adjustment may, for example, be accomplished by observation of the test target image through a microscope placed behind the analysing element or by optimizing the measured MTF values at a high spatial frequency when the test target or the analysing element is rotated.

NOTE Especially with electro-optical imaging systems, a measurable image rotation can occur [see also ISO 9336 (all parts)].

5.3.9 Signal-to-noise ratio

Noise sources that degrade the measured OTF include:

a) noise produced in the radiation detector and the circuits of the signal processor;

b) quantum noise of the input irradiance;

c) in the case of electro-optical imaging systems, internal noise sources of the test specimen;

d) fixed pattern noise.

The effects of these noise sources can be overcome by combinations of temporal and spatial integration.

In order to minimize problems with noise, the level of the test pattern, irradiance and the size of the analysing element shall be as large as allowed by the required spatial frequency range, the linearity and isoplanatism of the test specimen and the required measuring accuracy.

The actual signal-to-noise ratio can be estimated by monitoring the output signal of the radiation detector.

If a slit is used, an optimum slit width can be selected in order to get an optimum signal-to-noise ratio. If r_m is the highest spatial frequency to be measured, a useful optimum slit width, b_{opt}, is

$$b_{opt} = 1/2r_m$$

Ripple arising from the radiation source or from the ambient light can cause similar inaccuracies and shall be avoided wherever possible.

5.4 Particular measuring conditions

5.4.1 Azimuths

At every off-axis position, the measurement is generally made in the radial and tangential azimuth of the test object. Other azimuths (e.g. 45° direction) may also be selected.

5.4.2 Selection of image heights or field angles

It is recommended that values be selected from Table 2.

Table 2 — Recommended values for image height and field angle

Image height h'	Field angle ω
0	0
0,3 h'_{max}	0,3 tan ω_{max}
0,5 h'_{max}	0,5 tan ω_{max}
0,7 h'_{max}	0,7 tan ω_{max}
0,85 h'_{max}	0,85 tan ω_{max}
h'_{max}	tan ω_{max}

In Table 2, h'_{max} is the maximum specified image height and ω_{max} is the maximum specified field angle.

The set of image heights in Table 2 shall be used in intercomparisons of OTF results. However, a different set of image heights may be selected for special applications.

5.4.3 Reference angles of the test specimen

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

The reference angles giving maximum and minimum modulation transfer factor at 0,7 h'_{max} (0,7 tan ω_{max}) for a given spatial frequency, r_0, shall be determined, while r_0 shall be selected reasonably (often smaller than spatial frequency used for focusing).

As long as the difference of the extreme values of the measured MTFs 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 MTF value at $\pm$0,7 h'_{max} (0,7 tan ω_{max}). Otherwise the system should be tested for several reference angles depending on the type of test specimen and its application [see ISO 9336 (all parts)].

6 Corrections to measured data

6.1 Normalization

Although the OTF is by definition normalized to have the value unity at zero spatial frequency, it is often impossible to do so exactly during the measurement. This problem can occur if the analysed area is restricted in size and no value of OTF at zero spatial frequency is available.

However, provided the veiling glare introduced by the system under test is negligible, and that there are also no truncation errors, it is possible to normalize the curve within the required measurement accuracy.

6.2 Correction of the frequency scale

When making off-axis measurements with a grating test target positioned in the focal plane of a collimator, a correction of the frequency scale shall be performed. The frequency scale shall be reduced by a factor $\cos^2 \omega$ if the grating is in tangential azimuth, or by a factor $\cos \omega$ if the grating is in radial azimuth. In addition, a change in the slit width may be necessary. No correction is required when testing afocal systems.

6.3 Correction of the measured modulation

The amplitudes of the spatial frequency spectra of both the test target and analysing element affect the measured result. If this is not done automatically by the analyser, their influence shall be eliminated by correcting the measured result.

EXAMPLE For an object or scanning slit of width b, the measured uncorrected MTF result, $T_m(r)$, may be corrected as follows:

$$T(r) = T_m(r) \left[\frac{\sin(\pi rb)}{\pi rb} \right]^{-1}$$

where b and r refer to the same measurement plane.

If non-sinusoidal gratings are used as a test target, all spatial frequencies except the fundamental frequency of the target shall either be filtered out or their influence on the measured result eliminated by calculation.

6.4 Auxiliary imaging systems

If relay lenses are used in the measurement of the MTF of electro-optical components or of other systems that have incoherent coupling between the components of that system, the measured uncorrected MTF result, $T_m(r)$, shall be corrected by division by the MTFs, $Ti(r)$, i.e. $T_1(r)$, $T_2(r)$, etc., of the relay lenses and any other component:

$$T(r) = \frac{T_m(r)}{\Pi \ T_i(r)} \quad (1)$$

7 Presentation of OTF data

7.1 General

OTF data shall be presented in the form of graphs or tables accompanied by details of the measuring conditions and the estimated measurement accuracy. The presentation shall ensure an easy and quick intercomparison of OTF data from different laboratories and with similar imaging systems. Therefore, several selected forms of presentation are recommended. The particular presentation chosen depends on the imaging system and the measuring conditions and is specified in ISO 9336 (all parts).

The recommendation given below refers not only to OTF data that result from measurement, but also to calculated OTF data. Thus, an easy comparison between measured and calculated OTF data can be achieved.

7.2 Statement of identification and measuring conditions

The I-state of the test specimen shall be sufficiently defined to allow exactly repeatable measuring conditions in any laboratory. Therefore, a complete list of the values of all parameters that determine the measuring conditions shall be given.

The report shall include the following particulars:

a) the name of the laboratory;

b) the type of result (e.g. measurement, calculation);

c) the specification of the test specimen, i.e. type, number, etc.;

d) the focal length;

e) the *f*-number or numerical aperture;

f) the reference mark;

g) the maximum image height, h'_{max}, or maximum field angle, ω_{max};

h) the image scale and local image scale;

i) the reference plane;

j) the reference angle of the test specimen;

k) the spectral and angular radiation data;

l) the object height or field angle;

m) the azimuth (e.g. radial, tangential);

n) the focusing criterion and datum plane;

o) the measurement plane;

p) the spatial frequency range or set of discrete spatial frequencies;

q) the plane, or space, to which the spatial frequency scale applies.

Depending on the test specimen, additional measuring conditions shall be reported. Detailed lists are given in ISO 9336 (all parts).

These may include:

— any additional optical elements;

— the temperature, humidity and other environmental conditions;

— the operating voltages for electro-optical components.

7.3 Graphical presentation of OTF data

The OTF, which can be split into its MTF and PFT (see ISO 9334), should be presented in a two-dimensional form. In most cases only the MTF is available and will be presented. If both the MTF and PTF are to be presented, this may be done in one common graph or in two separate graphs. Two separate graphs should be used if there is any possibility of ambiguity.

It is recommended that the OTF be plotted as a function of the spatial frequency, image height, h', or field angle, ω. The use of other variables should be restricted to special imaging systems or special applications.

Both axes should be linear and start from zero.

When plotting the PTF, the zero point (at zero spatial frequency) should be in the centre of the ordinate. From there the PTF should be plotted in a ±180° (±π) range. Positive PTF values should represent a shift of the corresponding spatial frequencies towards larger radial distances or field angles.

Any linear term in the measured PTF shall be subtracted before presentation (see ISO 9334) such that the PTF at zero spatial frequency starts with a horizontal line. If this is done, the derivative of the PTF with respect to spatial frequency will be zero at zero spatial frequency. Although it is sometimes difficult to determine the linear term precisely, this should be done as well as possible in order to enable comparisons.

The spatial frequency shall be quoted in mm^{-1} or in $mrad^{-1}$. The field angle shall be quoted in mrad and radial distances given in mm.

The maximum value of the abscissa variable should be set to 1, 2 or 5 times 10^{x}, where x is an integer and depends on the imaging system and the abscissa variable. Detailed recommendations for particular imaging systems are given in ISO 9336 (all parts).

When both radial and tangential OTF curves are shown on the same graph, it is recommended that the radial OTF be drawn as a continuous line and the tangential OTF as a broken line. A typical presentation is shown in Annex A.

When the OTF results are presented in graphical form, the relevant measuring conditions, listed in 7.2, shall be incorporated in the graph, for example as a graph in a corner of the graph. Furthermore, a statement of accuracy of measurement shall be included.

7.4 Numerical presentation

The numerical presentation of OTF data shall cover the same ranges as given above for graphical presentations (see A.4).

8 Accuracy checks

Experience gained in the measurement of OTF indicates the need to exercise great care in the calibration and use of the equipment to ensure an acceptable accuracy of measurement. Accuracy of measurement can also depend on the repeatability of setting of variable parameters on the test specimen.

While overall accuracy can be assessed by the use of standard test specimens, these only operate within a limited I-state. More basic tests are needed to determine the accuracy of radiometric and geometrical parameters and to quantify the errors likely to arise from the relay optics and environmental factors.

The following parameters need to be considered when calibrating OTF measuring instruments.

a) Radiometry:

   1) spectral responsivity,

   2) coherence of test target,

   3) linearity,

   4) range of operation,

   5) stray light sensitivity,

   6) light fluctuations,

   7) test target density.

b) Geometry:

   1) width, length and straightness of test target structure,

   2) bench metrology,

   3) alignment of pattern and analyser,

   4) focusing accuracy.

c) Auxiliary optics:

   1) collimators,

   2) relay optics.

d) Environment:

   1) atmospheric turbulence,

   2) temperature,

   3) humidity,

   4) vibration.

e) Verification devices:

   1) slits, test target,

   2) standard and audit lenses,

3) phase plates (for incoherence tests),

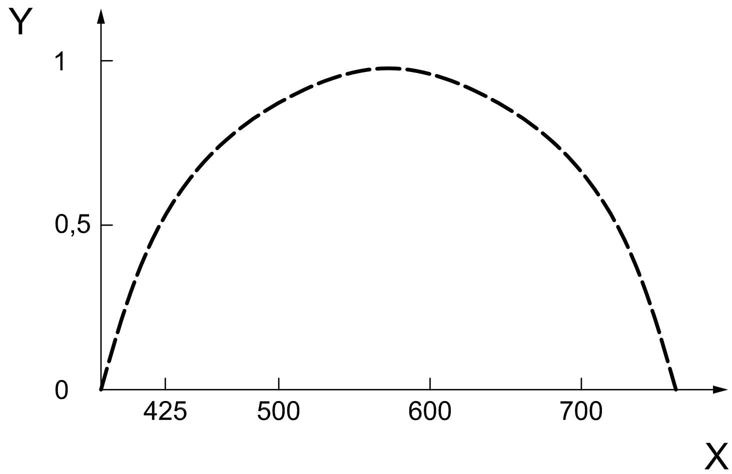
4) neutral density and colour filters.

Annex A
(informative)

Examples of the presentation of OTF data

A.1 Example of specification of image state

Laboratory	ISO
Measurements	MTF and PTF
Specimen	isogon f/2, $f = 35$ mm, Ser. No. 000123
Maximum image height (h'_{max})	22 mm
Image scale	0
Reference plane	lens mounting flange
Reference mark	red arrow on housing
Reference angles	0°, 90°, 180°, 270°
Spectral and angular data	spectral response A, Figure A.1
Image heights	0 h'_{max}; 0,5 h'_{max}; 0,7 h'_{max}; 0,85 h'_{max}; 1,0 h'_{max}
Azimuth	radial and tangential
Focusing criterion (datum plane)	maximum MTF at 20 mm^{-1} $h' = 0$ mm spectral response A reference angle 0° tangential azimuth
Measurement planes	datum plane, datum plane +5 µm, datum plane −5 µm
Measurement accuracy	±0,03 for MTF, ± 5° tor PTF
Spatial frequencies refer to	image plane
Spatial frequency range	0 mm^{-1} to 50 mm^{-1} in steps of 10 mm^{-1}



Key

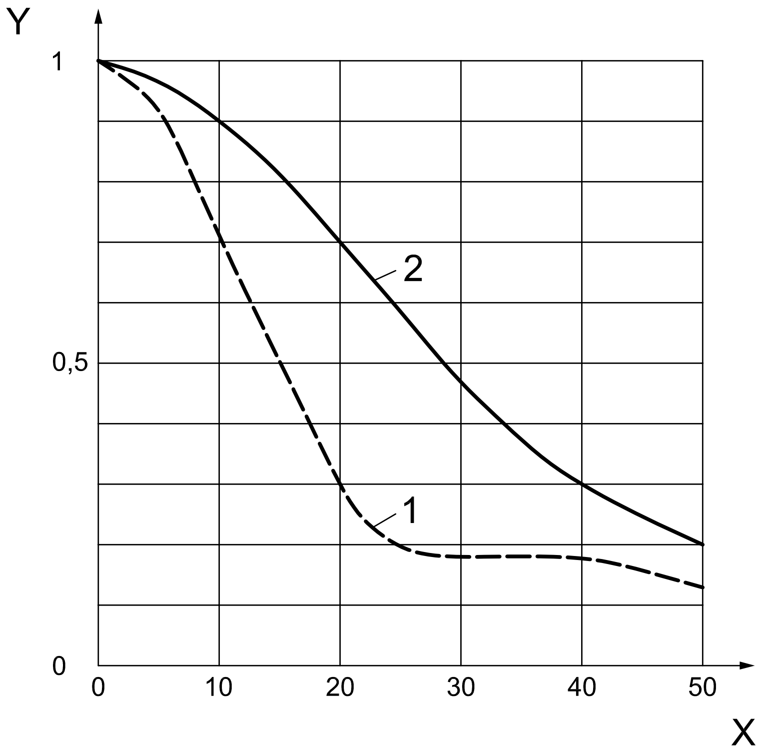
X wavelength, in nanometres

Y relative response

Figure A.1 — Spectral response A of the measuring system

A.2 Example of graphical presentation of OTF as a function of spatial frequency

Laboratory	ISO LAB
Specimen type	isogon
Serial No.	000123
Reference angle	270°
Image height	6 mm
Azimuth	R and T
Measurement plane	datum
Spectral response	A
Aperture	*f*/2



Key

X spatial frequency, in mm^{-1}

Y MTF

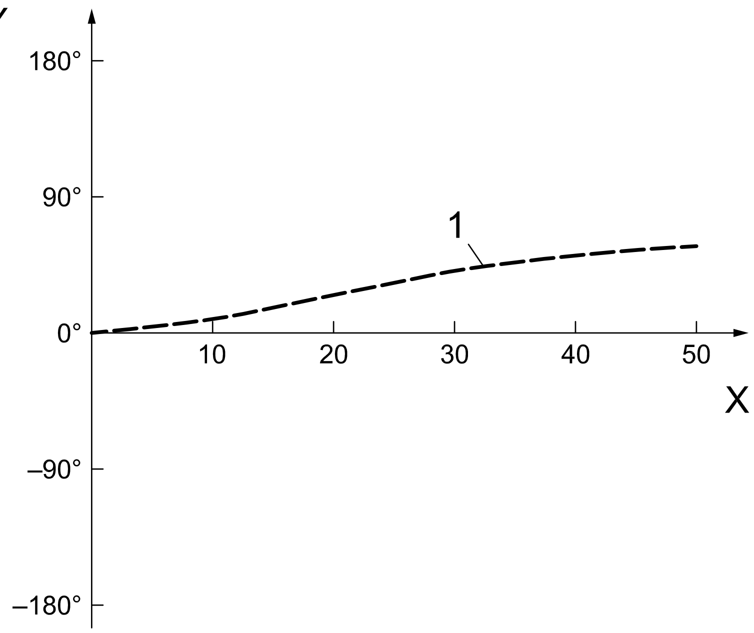
1 tangential

2 radial

Figure A.2 — MTF as a function of spatial frequency

A.3 Example of graphical presentation of PTF as a function of spatial frequency

Laboratory	ISO LAB
Specimen type Serial No.	isogon 000123
Reference angle	270°
Image height	6 mm
Azimuth	T
Measurement plane	datum
Spectral response	A
Aperture	*f*/2



Key

X spatial frequency, in mm^{-1}

Y PTF

1 tangential

Figure A.3 — PTF as a function of spatial frequency

A.4 Example of numerical presentation of MTF and PTF

Table A.1 — MTF and PTF values as a function of spatial frequency

Spatial frequency mm^{-1}	**MTF**(*s*) radial	**MTF**(*r*) tangential	**PTF**(*r*) degrees
0	1,00	1,00	0
10	0,89	0,72	8
20	0,65	0,31	21
30	0,40	0,18	35
40	0,29	0,18	49
50	0,22	0,13	56

Identification and test conditions:

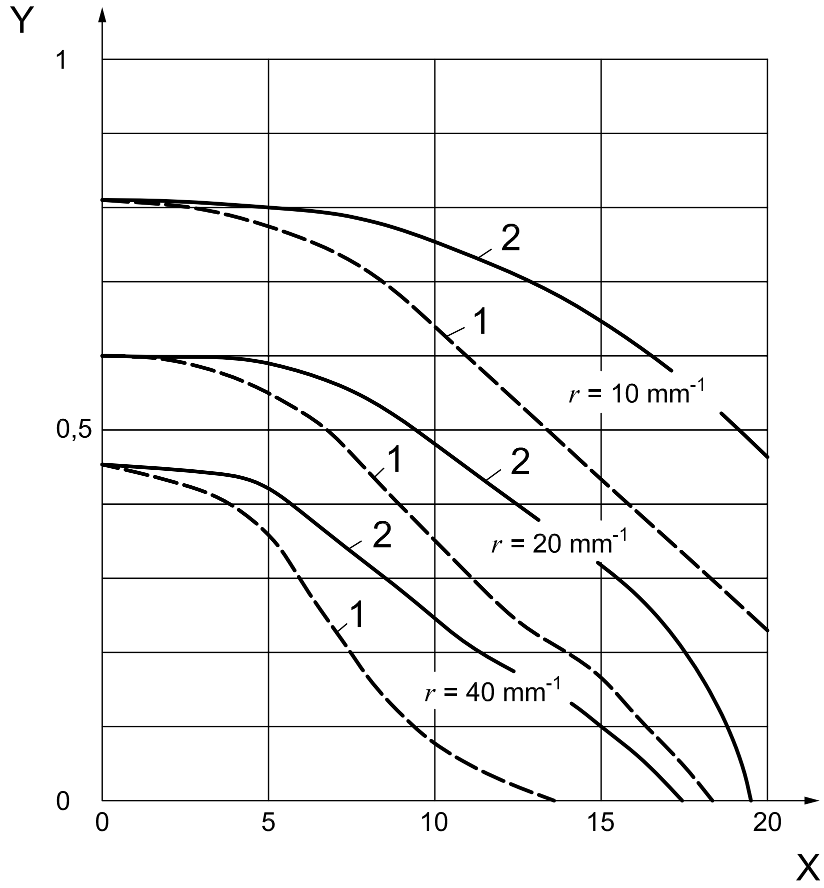
Laboratory	ISO LAB
Specimen type Serial No.	isogon 000123
Reference angle	270°
Image height	6 mm
Azimuth	R and T
Measurement plane	datum

Spectral response A

Aperture *f*/2

For other parameters, see the specification sheet.

A.5 Example of graphical presentation of MTF as a function of image height



Key

X image height, in mm

Y MTF

1 tangential

2 radial

Figure A.4 — MTF as a function of image height

Bibliography

[1] ISO 9336 (all parts), *Optics and photonics — Optical transfer function — Application*

[2] ISO 11421, *Optics and optical instruments — Accuracy of optical transfer function (OFT) measurement*

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