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Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement

Optique et instruments d'optique — Exactitude du mesurage de la fonction de transfert optique (OTF)

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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.

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.

International Standard ISO 11421 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 1 *Fundamental standards*.

Annex A forms an integral part of this International Standard.

Annexes B, C and D are for information only.

Introduction

The optical transfer function (OTF) is one of the main criteria used for objectively evaluating the image-forming capability of optical, electro-optical and photographic systems.

The terms used in the measurement of OTF are defined in ISO 9334, whilst ISO 9335 covers the actual principles and procedures of measurement. A further International Standard, ISO 9336, deals with specific applications in various optical and electro-optical fields and is in several parts, each dealing with a particular application.

Although ISO 9335 lists the main factors which influence the accuracy of OTF measurement and describes procedures which are aimed at achieving accurate and repeatable results, it does not cover in detail the techniques and procedures for evaluating the accuracy of OTF measuring equipment and for estimating the uncertainty in measurements made on specific imaging systems.

The present International Standard lists the main sources of inaccuracy in OTF measuring equipment and provides guidance on how these can be assessed and how the results of these assessments can be used in estimating the error band in any measurement of OTF. One of the aims in preparing this International Standard is to encourage the setting of more realistic uncertainty levels for the results of OTF measurements. Another is to encourage the use of methods of expressing the accuracy of OTF test equipment which recognize the fact that the accuracy of a particular measurement is a function of both the equipment and the test piece.

Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement

1 SCOPE

This International Standard gives general guidance on evaluating the sources of error in optical transfer function (OTF) equipment and in using this information to estimate errors in a measurement of OTF. It also gives guidance on assessing and specifying a general accuracy value for a specific measuring equipment, as well as recommending methods of routine assessment.

The main body of this International Standard deals exclusively with the modulation transfer function (MTF) part of the OTF. The phase transfer function (PTF) is dealt with relatively briefly in annex A.

2 NORMATIVE REFERENCE

The following standard contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

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

3 DEFINITIONS AND SYMBOLS

3.1 DEFINITIONS

For the purposes of this International Standard, the following definitions apply.

3.1.1 standard lens

Single- or multi-element lens which has been constructed with a level of accuracy which is sufficient to ensure that for precisely specified conditions of measurement the MTF will be equal to that predicted from theoretical calculations to an accuracy of better than 0,05 (MTF units).

NOTE - In order to achieve this accuracy, standard lenses are usually of simple construction and therefore of limited performance. An example of a widely used lens is the 50 mm focal length plano-convex lens described in reference [3]. This and several other standard test lenses (including afocal systems and lenses operating in the infrared wavelength bands) are available commercially.

3.1.2 audit lens

Single- or multi-element lens of stable construction whose accuracy of construction is not sufficient to enable the MTF to be predicted by calculation from design data (usually as a result of the complexity of the lens), but whose "accepted" values for the MTF under precisely defined measuring conditions have been obtained by measurements done by a reputable authority (preferably a national standards laboratory, if such a service is available).

3.2 SYMBOLS

Symbol	Meaning	Unit
h	object height	mm, mrad, degree
h'	image height	mm, mrad, degree
$\Delta h'$	error in image height	mm, mrad, degree
l	object conjugate	mm
l'	image conjugate	mm
$\Delta l'$	error in image distance	mm
Δz	departures from straightness of object slide	mm
$\Delta z'$	departures from straightness of image slide	mm
Δa	angular departure of object slide from perpendicularity to reference axis	rad
$\Delta a'$	angular departure of image slide from perpendicularity to reference axis	rad
ΔZ	total departure from ideal object plane	mm
$\Delta Z'$	total departure from ideal image plane	mm
M	magnification	dimensionless
r	spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
Δr	error in spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$m(r,h)$	rate of change of MTF with object focus (for image intensifier and similar systems)	mm^{-1}
$m'(r,h')$ or $m'(r,\omega)$	rate of change of MTF with image focus	mm^{-1}
$p'(r,h')$ or $p'(r,\omega)$	rate of change of MTF with image height	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$q'(r,h')$	rate of change of MTF with image distance	mm^{-1}
ω	field angle	mrad, degree
$\Delta\omega$	error in field angle	mrad, degree
f	focal length	mm
ψ	azimuth angle	degree
$\Delta\psi$	error in azimuth angle between slits	degree
R	(test lens focal length)/(collimator focal length) or (decollimator focal length)/(collimator focal length)	dimensionless
g'	width of slit referred to image plane	mm
L'	length of shorter slit referred to image plane	mm
MTF_c	MTF of relay lens	dimensionless
r_o	spatial frequency for zero field angle	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$n'(r, h')$	rate of change of MTF with spatial frequency	mm, mrad, degree
$\Delta MTF(r)$	error in MTF	dimensionless
$\Delta MTF_c(r)$	MTF error of the relay lens	dimensionless
ΔMTF_{rl}	MTF errors resulting from aberrations of relay lens error	dimensionless
Δl	error in setting collimator focus	mm
ΔMTF(random)	total error in MTF random sources	dimensionless
ΔMTF (systematic)	total error in MTF systematic sources	dimensionless
ΔMTF(total)	total error in MTF from all sources	dimensionless
$\Delta MTF(rand)_n$	error in MTF from nth source of random error	dimensionless
$\Delta MTF(syst)_n$	error in MTF from nth source of systematic errors	dimensionless

NOTE - The notation $m(r,h)$, $m'(r,h')$, $p'(r,h')$ etc. denotes that these parameters are functions of both spatial frequency r and image height h' or h (i.e. the value of the parameter will be different for different frequencies and different image heights).

4 SOURCES OF INACCURACY IN MEASURING EQUIPMENT

In this clause the main sources of inaccuracy in OTF measuring equipment are listed and the effects on a measurement of MTF described (brief comments on the measurement of PTF will be found in annex A).

4.1 GEOMETRY OF OPTICAL BENCH SYSTEM

The function of the optical bench is to provide a means for supporting the "test target unit", the "test specimen" and the "image analyser" in the correct geometrical relationship (i.e. that defined by the chosen I-state, in accordance with ISO 9334). To achieve this one normally relies on such things as the straightness of slideways, their parallelism to each other and/or to the surface to which the test specimen is referenced, the accuracy of angle scales etc. Departures from the assumed geometry result in deviations from the ideal I-state and therefore errors in the measured OTF. The important bench parameters depend on the test arrangement being used (note that for bench arrangements such as "nodal slide benches" which are not covered by this International Standard, the user must make his own assessment of errors). For the arrangements recommended in ISO 9335, the main sources of inaccuracy and the resulting MTF errors are as follows.

4.1.1 Object and image at finite conjugates

Both the test target unit (TTU) and image analyser slideways shall be straight and perpendicular to the "reference axis".

Departures from straightness and perpendicularity will produce departures from the ideal focal planes given by:

$$\Delta Z(h) = \Delta z(h) + h \cdot \Delta a$$

for the TTU and

$$\Delta Z'(h') = \Delta z'(h') + h' \cdot \Delta a'$$

for the image analyser, where h and h' are object and image heights, Δz and $\Delta z'$ are departures from straightness and Δa and $\Delta a'$ angular (radian) departures from perpendicularity to the reference axis, for the TTU and image analyser slideways respectively.

The combined effect is given by:

$$\Delta Z'(h')_{\text{total}} = \Delta Z'(h') + M^2 \cdot \Delta Z\left(\frac{h'}{M}\right)$$

where $M = \dfrac{h'}{h}$ is the magnification.

If $m'(r,h')$ is the rate of change of MTF(r) with focus, then the error in MTF is given by:

$$\Delta \text{MTF}(r) = m'(r,h') \cdot \Delta Z'(h')_{\text{total}}$$

Two further possible sources of error are in the accuracy with which the image height h' is set and the accuracy with which the object and/or image distances are set. The error in MTF is in this case given by (assuming image height and image distance are the parameters set):

$$\Delta \text{MTF}(r) = p'(r,h') \cdot \Delta h' + q'(r,h') \cdot \Delta l'$$

where $\Delta h'$ and $\Delta l'$ are the errors in image height and image distance respectively and p' and q' are the corresponding rates of change in MTF. Usually p' and q' are small and this source of error may be ignored (i.e. errors will be less than 0,01 in MTF units).

4.1.2 Infinite object and finite image conjugates

Similar considerations as for 4.1.1 apply except that there is only a single slideway. Departures from the ideal focal plane are given in this instance by:

$$\Delta Z'(h')_{\text{total}} = \Delta z'(h') + h' \cdot \Delta a'$$

and the corresponding error in MTF is given once again by:

$$\Delta \text{MTF}(r) = m'(r,h') \cdot \Delta Z'(h')_{\text{total}}$$

Errors may also arise from errors in setting image height or field angle (whichever is used in defining the I-state) and in setting the object distance to be infinity. These give MTF errors as previously, i.e.:

$$\Delta \text{MTF}(r) = p'(r,h') \cdot \Delta h' + q'(r,h') \cdot \Delta l'$$

or, if field angle rather than image height is specified:

$$\Delta \text{MTF}(r) = p'(r,\omega) \cdot \Delta\omega + q'(r,h') \cdot \Delta l'$$

In the above equations h', $\Delta l'$, p' and q' are as defined in 4.1.1, ω is the field angle and $\Delta\omega$ is the error in the field angle. The value of $\Delta l'$ shall be determined from the known departure of the object conjugate from infinity. The relevant equation is:

$$\Delta l' = \frac{f^2}{l}$$

where f is the focal length of the lens and l is the actual object conjugate.

Usually errors in MTF from these latter two sources are small and may be ignored except where, instead of using a collimator, a very long object conjugate is used on the assumption that it provides a sufficiently close approximation to an infinite conjugate.

4.1.3 Infinite object and image conjugates

With the recommended bench arrangement for this type of measurement (see ISO 9335) the separation between image analyser and decollimator should not change as the image angle varies. There is therefore no MTF error resulting from a change in focus setting with image angle (or field angle).

If bench arrangements are used where this error can occur, or, if as a result of mechanical flexing of the focal slide which supports the decollimator and image analyser their separation may change, then an error in the MTF may result, given by:

$$\Delta \text{MTF}(r) = m'(r,\omega) \cdot \Delta z'(\omega)$$

where $\Delta z'(\omega)$ is this mechanical error, and $m'(r,\omega)$ is the rate of change of MTF with focus.

Other sources of error are inaccuracies in setting field angle and in setting the object distance to be infinity. The resulting MTF errors are given by the relevant equations of 4.1.2, i.e.:

$$\Delta \text{MTF}(r) = p'(r,\omega) \cdot \Delta\omega + q'(r,h') \cdot \Delta l'$$

whereas before

$$\Delta l' = \frac{f^2}{l}$$

4.1.4 Image intensifiers and other systems with physically defined object and/or image surfaces

An accepted procedure when testing this type of system is to refocus the test target onto the object plane and/or the image plane onto the image analyser, for every test position in the image/object plane. With this procedure, focus errors arising from mechanical bench errors are eliminated. The only other source of error is from incorrectly setting the specified test positions in the object or image surfaces. The resulting MTF errors are usually negligible, and are given as in 4.1.1 by:

$$\Delta\text{MTF}(r) = p'(r,h') \cdot \Delta h'$$

If a test procedure is used where no refocusing is carried out when the object/image position is changed and reliance is placed on the TTU and image analyser slideways being straight and parallel to their respective object/image surfaces, then MTF errors are given by:

$$\Delta\text{MTF}(r) = m(r,h)[\Delta z(h) + h \cdot \Delta a] + m'(r,h')[\Delta z'(h') + h' \cdot \Delta a']$$

4.1.5 Mounting of test piece

The test piece may not always locate exactly as intended on the mount to which it is attached on the equipment. This will introduce some variability in the results of a sequence of measurements where the test piece has been removed from and remounted on the equipment between each measurement. The main effect is likely to be a small tilt of the image plane. The effect on the measured MTF, which can be very significant, is given by the same equations as for angular errors in the slideways (see 4.1.1).

4.2 AZIMUTH CHANGING

With most OTF equipments a change in measurement azimuth is achieved by rotating the TTU and the image analyser. This rotation can result in a movement of the TTU and or the image analyser along the direction of the axis of rotation. This will produce a focus change which will be denoted as:

$\Delta z(\psi)$ and $\Delta z'(\psi)$,

for the TTU and image analyser respectively, where ψ is the azimuth angle. The MTF error resulting from this focus change is given in 4.2.1 to 4.2.4 for each of the bench configurations.

4.2.1 Object and image at finite conjugates

$$\Delta\text{MTF}(r) = m'(r,h')\left[\Delta z'(\psi) + M^2 \cdot \Delta z(\psi)\right]$$

4.2.2 Infinite object and finite image conjugates

$$\Delta\text{MTF}(r) = m'(r,h')\left[\Delta z'(\psi) + R^2 \cdot \Delta z(\psi)\right]$$

where R is the ratio $\dfrac{\text{(test lens focal length)}}{\text{(collimator focal length)}}$.

Usually R^2 will be small and the second term in the brackets may be ignored.

4.2.3 Infinite object and image conjugates

$$\Delta\text{MTF}(r) = m'(r,\omega)[\Delta z'(\psi) + (M \cdot R)^2 \Delta z(\psi)]$$

where R is the ratio $\dfrac{\text{(decollimator focal length)}}{\text{(collimator focal length)}}$) and M is the magnification of the test telescope.

4.2.4 Image intensifiers and other systems with physically defined object and/or image surfaces

If a test procedure is used where the test target is refocused on to the object plane and/or the image plane on to the image analyser, for every test azimuth (see 4.1.4) then no errors will result. If a test procedure is used where no refocusing is carried out when the object/image azimuth is changed, then MTF errors are given by:

$$\Delta\mathrm{MTF}(r) = m(r,h) \cdot \Delta z(\psi) + m'(r,h') \cdot \Delta z'(\psi)$$

4.3 ALIGNMENT (ORIENTATION) OF TTU AND IMAGE ANALYSER

If both the TTU and the image analyser use mask patterns which are not circularly symmetric, then their relative orientation is important. Usually one or both of the masks is in the form of a slit perpendicular to the scan direction. The effect of any angular misalignment $\Delta\psi$ between the two (see figure 1) will result in an effective increase in width of the slit, given by:

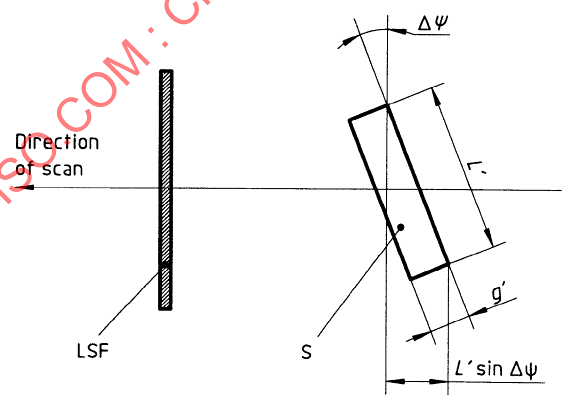
$$\Delta g' = L' \cdot \Delta\psi$$

where L' is the length of the shorter of the two slits, referred to the image plane. The error in MTF resulting from this is given by:

$$\Delta\mathrm{MTF}(r) = \pi \cdot r \cdot L' \cdot \Delta\psi \cdot \mathrm{MTF}(r) \cdot \left(\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{tan(\pi \cdot r \cdot g')} \right)$$

where g' is the assumed width of the slit, referred to the image plane.

It is important to note that in some types of equipment a combination of a slit and a grating is used to generate a periodic target whose spatial frequency can be altered by changing the orientation of the grating with respect to the slit. Spatial frequency errors will usually result from any errors in the relative orientation of the slit and grating. The user must make his own assessment of the effect of such errors (see 4.6 for the effect of spatial frequency errors on MTF).



$$W = g' + L'\sin\Delta\psi$$

Key

LSF Line spread function
S Image analyser slit
L' Length of slit
g' Width of slit
$\Delta\psi$ Angular misalignment
W Effective slit width

Figure 1 - Errors from alignment of analysing slit with respect to object pattern

4.4 CORRECTION FACTORS

Correction factors are applied to MTF measurements to allow for the effect of equipment constants such as the finite width of target and/or analyser slits, the MTF of incoherently coupled relay lenses and the effect of off-axis measurement geometry on spatial frequency (see ISO 9335). Errors in MTF will occur either if these factors are not applied, or if there is an error in the value of the applied correction factor. Only the most common correction factors are considered here. However, these may be taken as examples of how to deal with other types of correction factor.

4.4.1 Slit width errors

Errors or uncertainties in the widths of slits will introduce errors in the measured MTF, given by:

$$\Delta \mathrm{MTF}(r) = \pi \cdot r \cdot \mathrm{MTF}(r) \left(\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{\tan(\pi \cdot r \cdot g')} \right) \cdot \Delta g'$$

where g' is the width of the slit, referred to the image plane and $\Delta g'$ is the error or uncertainty in its value.

4.4.2 Correction for MTF of incoherently coupled relay lenses

Incoherently coupled relay lenses are frequently used in equipment for measuring the MTF of electro-optical devices and systems such as image intensifier tubes. The reciprocal of the MTF of these relay lenses is applied to the measured MTF as a correction factor. Any errors in the value of MTF of such relay lenses will therefore introduce errors into the final MTF value for the system under test. If the error in the MTF of such a relay lens is $\Delta \mathrm{MTF}_c(r)$ and the actual value of its MTF is $\mathrm{MTF}_c(r)$, then the error in the MTF of the test system is given by:

$$\Delta \mathrm{MTF}(r) = \mathrm{MTF}(r) \cdot \frac{\Delta \mathrm{MTF}_c(r)}{\mathrm{MTF}_c(r)}$$

where MTF(r) is the MTF of the system.

Similar considerations apply to other measurement situations where a correction is applied for the MTF of a device in the measurement train.

4.4.3 Spatial frequency correction for field angle

In making off-axis measurements with a grating test pattern positioned on the axis and in the focal plane of a collimator, a correction of the frequency scale should be performed (this also applies whenever frequency is measured in this plane). The corrected frequency is given by:

$r = r_o \cdot \cos^2(\omega)$ for the tangential azimuth and

$r = r_o \cdot \cos(\omega)$ for the radial azimuth, where r_o is the on-axis frequency

Errors in the value of r will be produced by errors in the value of ω the field angle. The values of these errors are given by:

$$\Delta r = 2 \cdot r_o \cdot \sin(\omega) \cdot \cos(\omega) \cdot \Delta\omega$$

and

$$\Delta r = r_o \cdot \sin(\omega) \cdot \Delta\omega$$

The effect of such errors on the MTF can be calculated in the manner indicated in 4.6.

4.5 FOCUS ERROR

An error or uncertainty in focus of $\Delta z'$ (referred to the image plane) will result in an MTF error or uncertainty given by:

$$\Delta \mathrm{MTF}(r,h') = m'(r,h') \cdot \Delta z'$$

where $m'(r,h')$ is the rate of change of MTF with focus for a spatial frequency r and an image height h'.

The value of $\Delta z'$ will depend on several factors. The most important of these are: the sensitivity of the focus control, the technique of focusing used, the spatial frequency at which the MTF is maximized (low frequency will generally result in a low focusing accuracy), the numerical aperture (NA) of the test lens, the MTF of the test lens, the signal/noise ratio associated with the particular equipment and test configuration.

Uncertainties in the focus position will normally only lead to small errors in MTF at the field position where the lens is focused (usually on-axis). However large errors may result at other field positions, particularly where astigmatism and/or field curvature are present.

4.6 SPATIAL FREQUENCY ERRORS

An error Δr in the spatial frequency will produce an MTF error given by:

$$\Delta \mathrm{MTF}(r,h) = n'(r,h') \cdot \Delta r$$

where $n'(r,h')$ is the rate of change of MTF with spatial frequency. Some sources of spatial frequency errors are: calibration errors, non-linearity and/or zero offset in transducers or mechanisms generating the spatial frequency reading. Note that the relationship between spatial frequency in image and object space may change with image height in the presence of distortion.

4.7 RESIDUAL ABERRATIONS IN RELAY OPTICS

Any optical system in the MTF measurement chain which is coherently coupled to the system under test (e.g. collimators and image relay lenses) should be aberration-free, since corrections cannot be applied for their effect on the measured MTF.

Accurate assessment of the errors resulting from known residual wavefront aberrations in relay lenses require the aberrations of the test system to also be known. Moreover, complex calculations are required for its determination.

If information is available about the MTF errors $\Delta \mathrm{MTF}_{rl}(r)$ which would result from the aberrations of the relay system when testing a diffraction-limited lens with the same NA and aperture diameter as the test system, then this represents the largest error which will be introduced into the measurements from this source. The value of $\Delta \mathrm{MTF}_{rl}(r)$ can either be measured directly or can be computed from the measured aberrations of the relay lens.

Unfortunately this approach will overestimate the errors when the system under test is poorly corrected.

4.8 SPECTRAL CHARACTERISTICS

The mismatch between the actual and desired spectral response characteristics of the measurement equipment will introduce errors in the measured MTF. The magnitude of the errors will depend on the sensitivity of the MTF of the system under test to the particular mismatch.

If the design data for the system under test is available and the characteristics (or likely characteristics) of the spectral mismatch are known, then the associated MTF errors can be calculated using a computer program for calculating polychromatic MTF. An alternative to this is to estimate the errors from the results of MTF measurements made using appropriate narrow-band filters (see 5.4). Where a spectral mismatch is known to occur and where the resulting error cannot be determined, this should be clearly indicated on the measured MTF data and a curve provided showing the actual overall spectral response characteristics used. It is important to realize that even low levels of response, at wavelengths where the response is assumed to be zero, can result in a significant error in the measured MTF. This is particularly so when making measurements on optical systems designed for use with monochromatic radiation, which may have little or no correction for chromatic aberrations. It can be a mistake to attempt to use a filter with a very narrow bandwidth for such measurements since this increases the relative effectiveness of any transmission outside the intended pass band.

4.9 EXTENT OF TEST TARGET AND/OR SCAN

If the correct boundary conditions are not satisfied during a measurement of MTF, an error will result. It is difficult to estimate in a particular case what error can be introduced in this way. However there are several tests that can be made to check if this is likely to be a significant source of error. In general terms, an increase or decrease in the lateral extent of a test target or analysing mask and (where applicable) the extent of a scan, should produce no change in the absolute signal level, or in the measured MTF, if the boundary conditions are correct. The minimum or maximum acceptable extent of test targets etc. is related to the size of the point spread function. An approximate knowledge of this can allow one to determine if the boundary conditions for a particular measurement technique are satisfied.

4.10 ANGULAR RESPONSE CHARACTERISTICS OF IMAGE ANALYSER

For the result of an MTF measurement to be correct, the image analyser must respond to the full angular cone of radiation from the test system. Any truncation, or nonuniform attenuation of this response, will introduce errors in the measurement. The polar response of an image analyser should be measured and the possible errors evaluated using the method described in 5.7.

4.11 POLAR LUMINANCE/RADIATION CHARACTERISTICS OF OBJECT GENERATOR

Similar considerations apply as for the polar response of image analysers (4.10). The requirements are usually easier to satisfy in this instance, since in most situations the TTU is only required to uniformly illuminate the aperture of a collimator.

4.12 EQUIPMENT SIGNAL PROCESSING

Errors in the MTF measurement can arise from limitations and inaccuracies in the signal processing of the measuring equipment. The magnitude of such errors can be estimated from measurements carried out using standard test lenses or special artefacts such as accurately measured slits (see 5.6).

4.13 STRAY RADIATION

Stray radiation from such sources as room lighting may affect the performance of an equipment. This should be checked by the user and any undesirable sources of radiation eliminated or reduced to a level at which their effects are insignificant.

4.14 COHERENT RADIATION

The concept of OTF as it is dealt with in this International Standard applies only to objects which are illuminated incoherently. The use of coherently, or partially-coherently, illuminated test objects for the measurement of OTF will give incorrect results. No easy means of assessing the degree of coherence or partial-coherence of a test object exists. The necessary steps to avoid coherent illumination are part of the design of an equipment and are not dealt with in this standard. Apart from avoiding the use of coherent sources such as lasers, a necessary condition of illumination is that the numerical aperture (NA) of the optical system illuminating the test object shall be greater than the object-side NA of the test piece (for collimated radiation the pupil of the collimator shall also be greater than that of the test piece). When testing systems with large NAs (such as microscope objectives), care is required to ensure that this condition still holds. No such problem exists with self-luminous test objects.

4.15 BASELINE ERROR

If the signal baseline (i.e. zero level) used in a measurement of MTF is incorrect, the result can have significant errors.

Departures from the correct baseline are typically a result of sensitivity of the equipment to ambient lighting, uncompensated, or incorrectly compensated, detector dark current and signal offsets from misadjustment of the electronic circuits.

In many electro-optical systems the image normally sits on a non-zero background. Baseline errors occur if this background is incorrectly subtracted from the measured signal.

The accuracy of the baseline can be checked by comparing the assumed level with that obtained when the object generator source is switched off or when the test pattern is replaced by a blank pattern. The two levels should be the same.

5 METHODS OF ASSESSING LEVELS OF ACCURACY

In this clause techniques are described for making the quantitative measurements which enable a value to be given to the possible errors arising from some of the sources listed in clause 4. Alternative methods of making these measurements exist in most cases. They may be used provided they have the necessary accuracy.

Many of the measurements can be made using well-known techniques and are therefore not described in this International Standard.

In most instances both systematic and random errors exist, and both should be assessed.

5.1 GEOMETRY OF OPTICAL BENCH SYSTEM

5.1.1 Straightness of slideways

This refers principally to the overall flatness or straightness of the line or plane over which the image analyser and/or TTU move and which therefore defines the image and/or object planes.

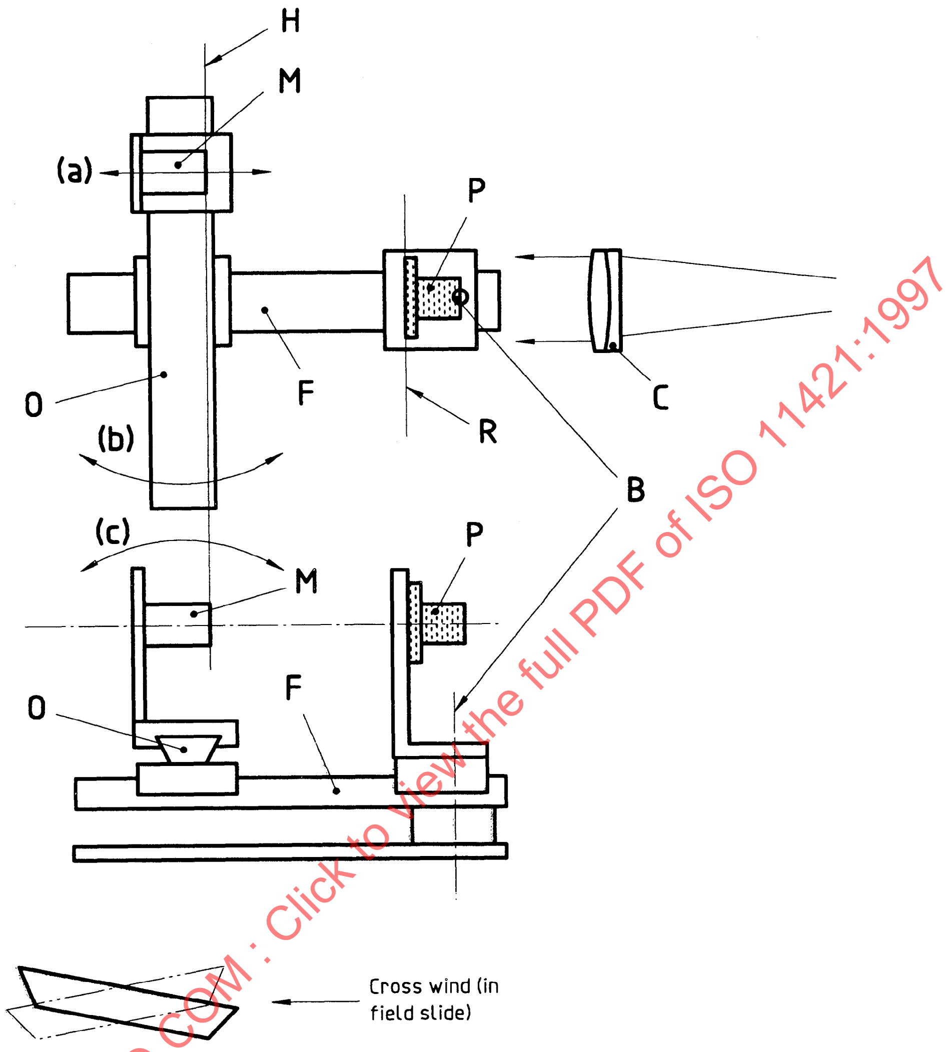
Departures from the ideal plane are usually caused by lack of straightness and/or crosswind (see figure 2) in the slideway(s) which carries the image analyser or TTU.

Various well-established techniques exist for measuring straightness and crosswind. The method recommended here is to make a direct measurement of their combined effect using a sensitive linear distance transducer and a reference straightedge or plane. The arrangement is illustrated in figure 3. The transducer is mounted in the position normally occupied by the image analyser or TTU, with the measuring probe along what would normally be their optical axes. The reference plane or straightedge is mounted parallel to what should be the image/object plane or measurement diagonal (i.e. perpendicular to the reference axis). The probe is arranged so that it measures directly the variation in distance between the reference plane or edge and what would be the positions of the image analyser or TTU as they move along the slideway.

The reference axis is usually taken as being an axis perpendicular to the surface on which the optical system reference mounting flange (or equivalent) will locate. The straightedge or reference plane is therefore set parallel to this, either using an autocollimator and suitable plane mirror(s), or in fact by mounting them directly on this surface.

This measurement technique gives results which include the effect of any overall angular deviation from perpendicularity to the reference axis.

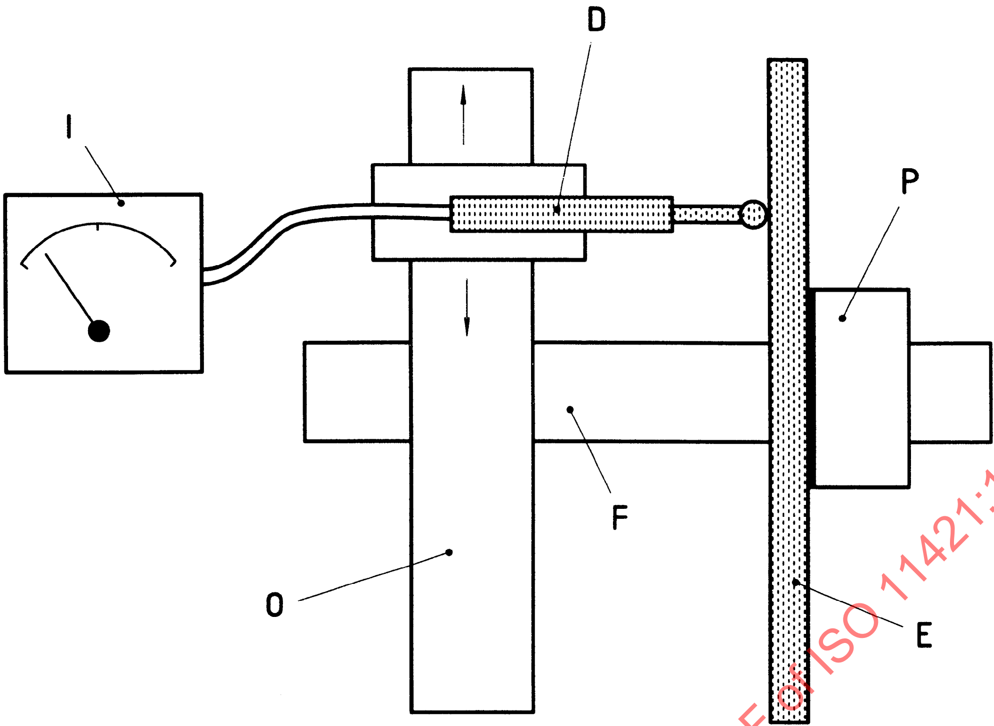
NOTE - for some optical systems the reference mounting surface may be parallel to rather than perpendicular to the reference axis (e.g. a lens with a cylindrical body concentric with its optical axis, may use the cylindrical surface as the reference mounting surface) and the alignment technique must be adapted accordingly.



Key

P Lens under test
R Lens reference surface (flange)
H Image plane
O Field slide
F Focal slide
M Image analyser
C Collimator
B Axis of rotation
(a) Straightness errors
(b) Slideway misalignment
(c) Cross wind errors

Figure 2 - Mechanical bench errors



Key

E Reference straightedge or flat
F Focal slide
O Image analyser slideway
P Fixture for test specimen
D Distance transducer
I Indicator

Figure 3 - Straightness and parallelism using distance transducer

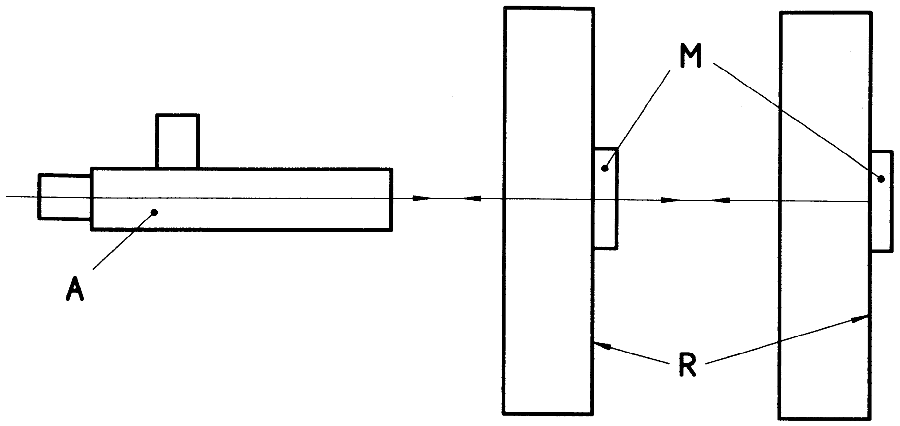
5.1.2 Parallelism of surfaces and/or perpendicularity to reference axes

An autocollimating telescope in conjunction with suitable plane mirrors can be used for checking that surfaces are parallel to each other.

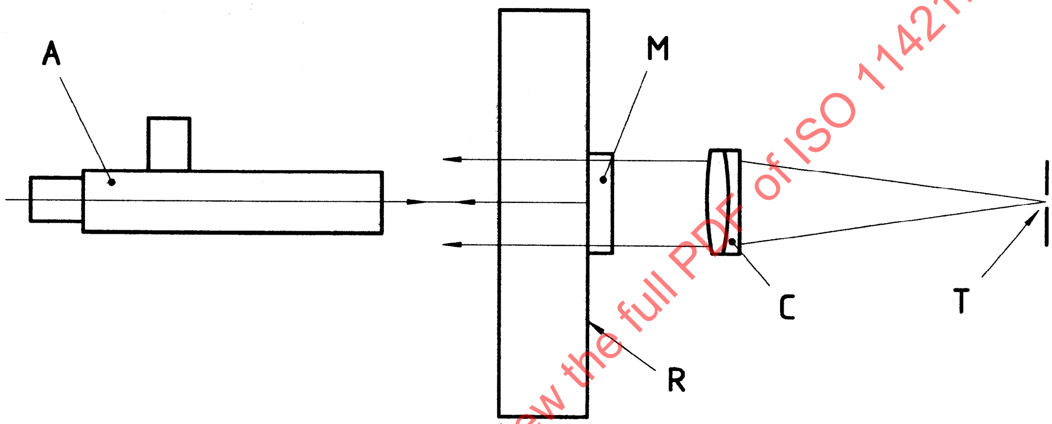
The same telescope (if suitably adjusted so that its autocollimating axis and alignment axis coincide) can be used for checking that a surface is perpendicular to the direction of a collimated beam (see figure 4).

Note that the collimator on an equipment can sometimes be used as an autocollimator on condition that some means is provided for viewing the target and the return image. A low power laser is also a simple alternative to an autocollimating telescope provided sufficiently long throws are available to give the desired angular accuracy.

Note that the angular repeatability with which a test piece is located on the equipment can be assessed using an autocollimator and a mirror attached to the test piece.



a) Parallelism of two reference faces



b) Perpendicularity of reference face to collimated beam

Key

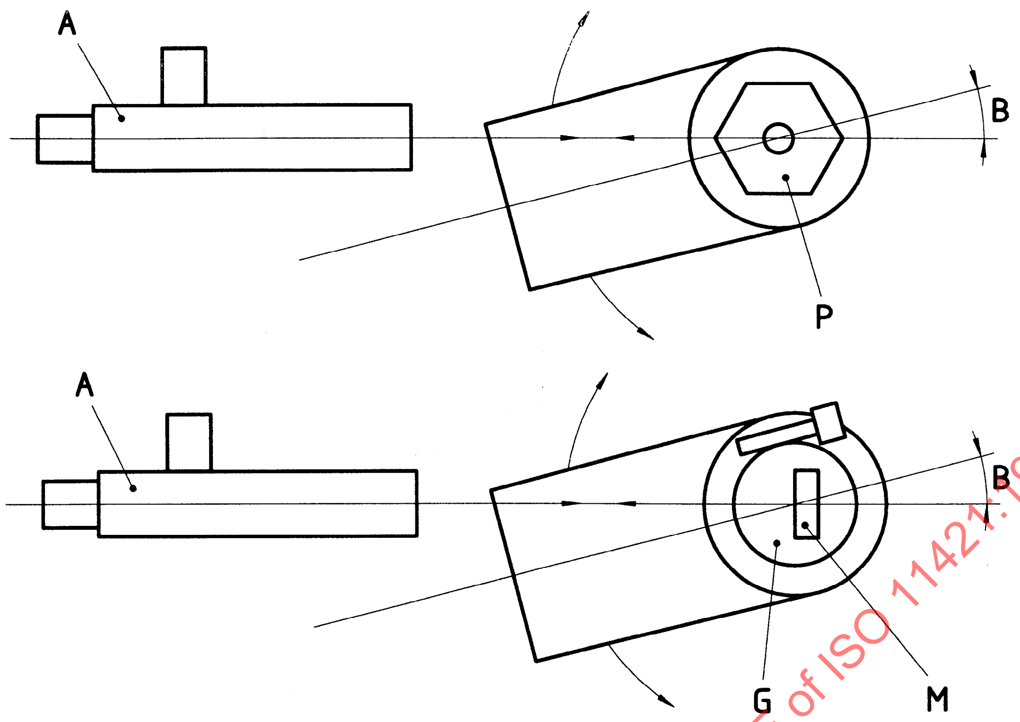
R Reference face
A Autocollimator
M Mirror
C Collimator
T Target

Figure 4 - Use of autocollimator for alignment of surfaces

5.1.3 Accuracy of rotation angles

Accuracy of angular rotation can be measured using an autocollimator in conjunction with an accurate mirror-polygon mounted on the rotating component, or in conjunction with a plane mirror and accurately calibrated goniometer table mounted on the rotating component. Both these methods are illustrated in figure 5.

Once again (see 5.1.2) a laser may be used instead of the autocollimator.



Key

A Autocollimator
P Calibrated reflecting polygon
M Mirror
B Angle of rotation
G Calibrated goniometer table

Figure 5 - Calibration of angular rotation

5.2 COLLIMATOR FOCUS (DEPARTURE FROM INFINITE OBJECT DISTANCE)

One approach to estimating the possible departure from collimation of a nominally collimated beam, is to determine by experiment the possible range of position settings for the TTU which the particular method of adjusting for collimation allows. If this range is $\pm \Delta l$, then the possible values for the object conjugate will be $\pm l$, where:

$$l = \frac{f^2}{\Delta l}$$

where f is the focal length of the collimator.

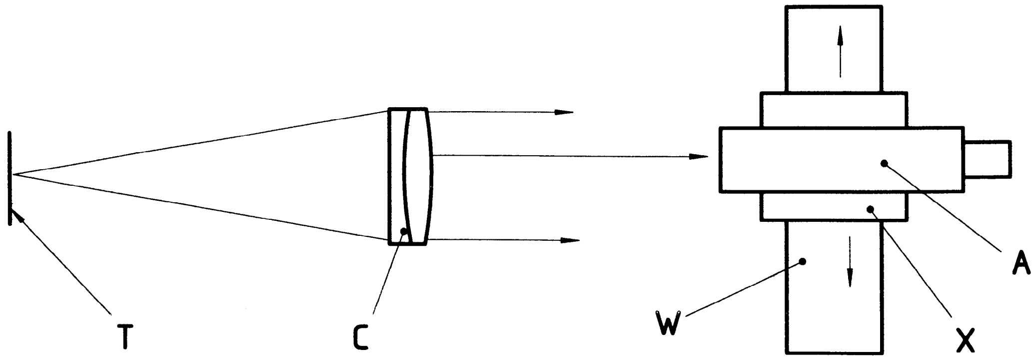
An alternative approach is to measure l directly using a suitable measuring device placed in the nominally collimated beam. Suitable devices are:

— a calibrated range-finder;

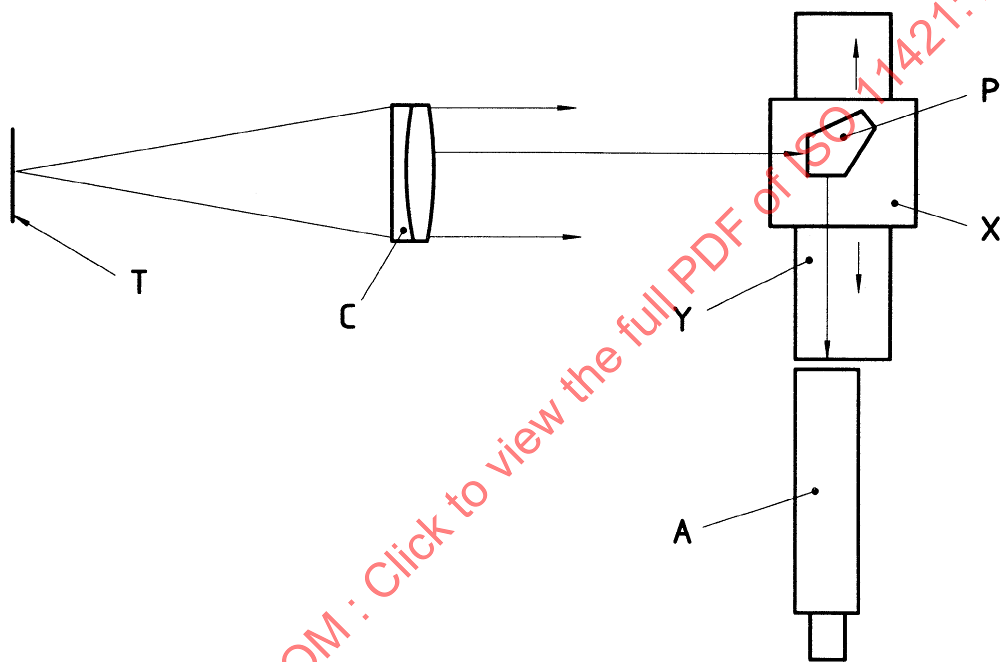
— a long focal length lens with a focusing screen (e.g. split-field prism) and calibrated focus settings. A reflex viewfinder camera with a telephoto lens may be used;

— an alignment telescope mounted on a high precision linear slideway at right angles to the axis of the collimated beam. This would measure the apparent angular aberration across the beam, from which the value of l can be calculated. The need for a precision slideway can be removed by keeping the telescope fixed and moving a pentaprism along the slideway as illustrated in figure 6.

Note that any of these devices for measuring collimation can themselves be checked using a distant object.



a) Use of alignment telescope and precision linear slideway



b) Use of pentaprism and telescope

Key

A Alignment telescope
C Collimator
T Plane of test target
P Pentaprism
W Precision slideway
Y Slideway
X Slideway carriage

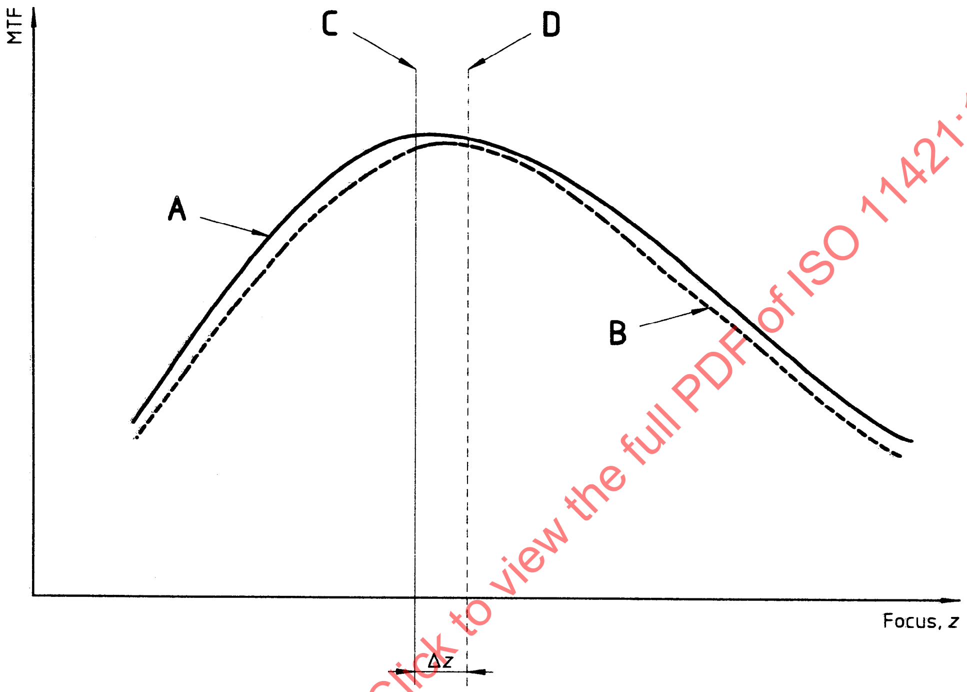
Figure 6 - Checking collimator focus

5.3 FOCUS SETTING

For a particular equipment, the accuracy with which the focus of the test lens is set depends on several factors. More specifically (as explained in 4.5), it depends on the focus technique, the focus criterion, the *f*/number of the test lens, the MTF performance of the test lens and the particular equipment configuration used (e.g. the collimator focal length, image analyser and TTU slit widths, spectral filter characteristics etc). The accuracy of focus setting should therefore be estimated under conditions where these variables are the same or similar.

The random errors in focusing can be estimated by measuring directly the standard deviation in focus position resulting from performing the focusing routine a suitably large number of times under the same or similar test conditions.

Systematic errors are more difficult to assess. The possible presence of such errors is best determined by using suitable standard test lenses and comparing the theoretical and measured through-focus MTF curves and their respective best focus positions. The procedure is illustrated in figure 7. The difference between the two best focus positions which gives the closest fit between the two sets of curves is the focus error. The measured through-focus curve and best focus position should of course be an average of several measurements. A comparison should be made for several numerical apertures in order to provide data which can be used for estimating systematic focus errors in different test situations.



Key

A Theoretical through-focus MTF
B Measured through-focus MTF
C Theoretical best focus
D Measured best focus
Δz Focus error

Figure 7 - Determination of systematic focus errors

5.4 SPECTRAL CHARACTERISTICS

If the design data for the system under test is available and the characteristics (or likely characteristics) of the spectral mismatch are known, then the associated MTF errors can be calculated using a computer program for calculating polychromatic MTF.

Alternative experimental methods are available for determining the errors resulting from spectral mismatch. These involve making several OTF measurements using different spectral filters and then processing the resulting data. These procedures are complicated and time-consuming and are not covered in this International Standard.

An indication of how sensitive a particular test specimen is to spectral mismatch can however be obtained by doing MTF measurements with two or more filters which produce spectral characteristics which span the range of the specified characteristics.

For example, if a spectral range of 0,48 μm to 0,64 μm is specified for a measurement but cannot be exactly matched and assuming ranges of say 0,45 μm to 0,7 μm and 0,5 μm to 0,6 μm can be generated, then the sensitivity to mismatch can be estimated by comparing the results of the MTF measurement in these two ranges.

The methods of evaluating errors described above require that the spectral response characteristics of the OTF equipment be known. This can be determined from the spectral characteristics of the source, the detector and any other components in the system if these are known. Alternatively it can be measured directly.

One method of making such a measurement is to use a set of narrow-band monochromatic filters which have been calibrated so that their relative integrated transmissions are known. The latter can be done by measuring the relative areas under the spectral transmission curves measured on a spectrophotometer.

These filters are then positioned in turn in the radiation path of the OTF equipment and the absolute value of the signal which corresponds to zero spatial frequency is measured. The relative value of this signal for the different filters, when corrected for their integrated transmissions, is a measure of the relative spectral response of the whole equipment.

It should be noted that for equipment which measures the LSF, the area under the non-normalized LSF curve corresponds to the zero spatial frequency signal.

5.5 EXTENT OF TARGET AND/OR SCAN

It is difficult to estimate in a particular case what error can be introduced in this way. However there are several tests that can be made to check if this is likely to be a significant source of error. In general terms, an increase or decrease in the lateral extent of a test target or analysing mask, and (where applicable) the extent of a scan, should produce no change in either the absolute signal level or the measured MTF, if the boundary conditions are correct.

The minimum or maximum acceptable extent of test targets etc. is related to the maximum extent of the point spread function. An approximate knowledge of this can allow one to determine whether the boundary conditions for a particular measurement technique are satisfied.

5.6 EQUIPMENT SIGNAL PROCESSING

The magnitude of such errors can be estimated from measurements carried out using standard test lenses (see 7.2), small aperture optics which are diffraction-limited, or special artefacts such as accurately measured slits.

When one or more standard lenses (or small aperture optics) are used, these should be selected to most closely resemble the type of lens being tested. Only on-axis measurements shall be made using focus conditions giving maximum MTF at the specified focusing spatial frequency.

Systematic errors are taken as the difference between the average of a number (8 or more) of measurements of MTF and the theoretical MTF values. Random errors are taken as the standard deviation for a number (8 or more) of MTF measurements. These measurements should be made without repeating the focusing procedure (i.e. at the same focus setting).

Accurately made slits are particularly appropriate for estimating measurement accuracy when evaluating equipment designed or configured for making measurements on images generated on screens. Examples are images produced on cathode ray tube (CRT) displays and on the output face of image intensifiers.

The MTF of a slit is given by:

$$\frac{\sin(\pi \cdot r \cdot g)}{(\pi \cdot r \cdot g)}$$

where g is the width of the slit and r is spatial frequency.

Systematic and random errors are determined in the same way as for standard lenses.

5.7 POLAR RESPONSE TO IMAGE ANALYSER

The method of assessing the adequacy of the polar response characteristics of the image analyser depends on exactly how it is used. Where the axis of symmetry (usually the optical axis) is always coincident with the principal ray, measurements with a standard lens of appropriate f/number can provide a good indication of likely errors from this source. Where the axis of the image analyser does not remain coincident with the principal ray for off-axis measurements, a standard lens may also be used. However in this case, in addition to the normal on-axis measurements, off-axis measurements should be simulated using one of the methods illustrated in figure 8. In the first of these, the image analyser is mounted on a precision rotary table arranged so that the image analyser slit is accurately positioned over the axis of rotation. MTF measurements are made with the standard lens (or an audit lens) always used on-axis, but with the image analyser rotated through an appropriate range of angles (i.e. angles up to the maximum field angles used with the equipment). The results should not depend on the angle of the image analyser, any variation with angle will be an indication of likely errors from this source.

The second method is similar in principle but has the advantage that it can be implemented directly on the equipment. It uses a standard or audit lens mounted in a gimbal which allows the orientation of the lens to be adjusted so that it is always used on-axis even when the equipment is set for off-axis measurements. A plane mirror on the lens mount, used in conjunction with an autocollimator or laser, can be used to set the test lens to the correct angle.

6 CALCULATION OF OVERALL ACCURACY OF A MEASUREMENT

The overall accuracy of a particular measurement of MTF should be calculated as the combination of the total random uncertainty and the total systematic uncertainty. This may be written as:

$$\Delta\mathrm{MTF(total)} = \Delta\mathrm{MTF(random)} + \Delta\mathrm{MTF(systematic)}$$

where the random uncertainty is the square root of the sum of the squares of all random errors:

$$[\Delta\mathrm{MTF(random)}]^2 = [\Delta\mathrm{MTF(rand)}_1]^2 + [\Delta\mathrm{MTF(rand)}_2]^2 + \ldots$$

and the systematic uncertainty is the algebraic sum of all systematic errors:

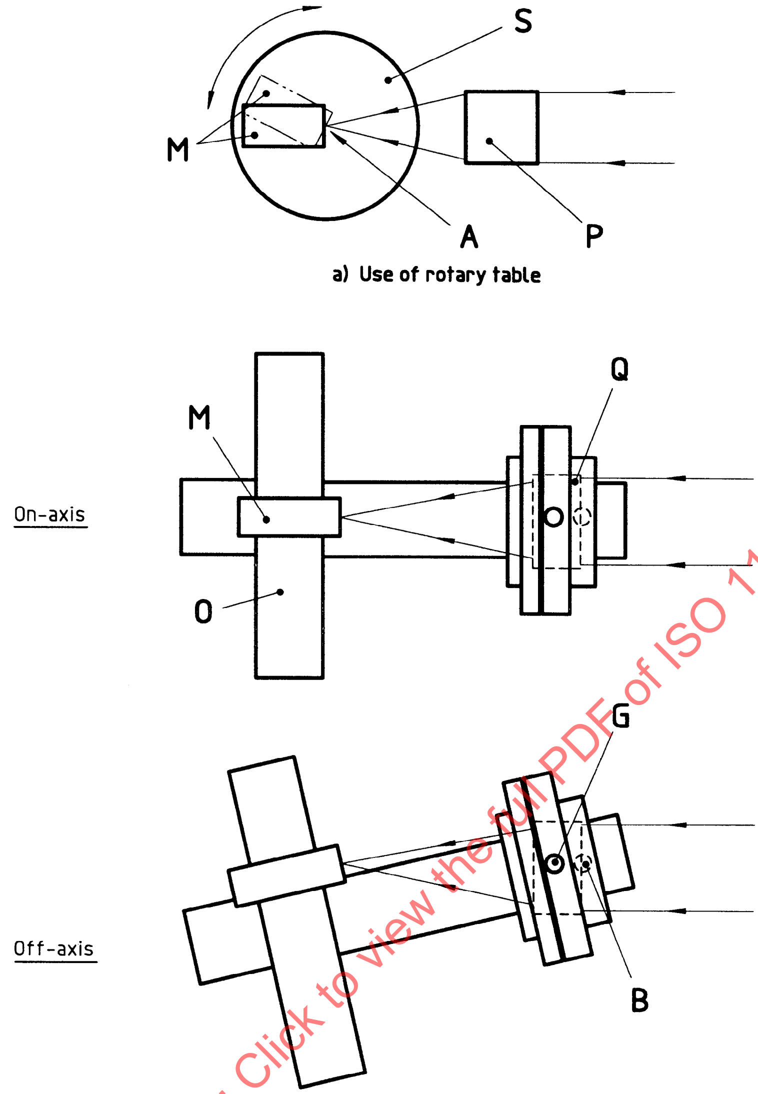
$$\Delta\mathrm{MTF(systematic)} = \Delta\mathrm{MTF(syst)}_1 + \Delta\mathrm{MTF(syst)}_2 + \ldots$$

$\Delta\mathrm{MTF(rand)}_n$ are the individual sources of random errors

and

$\Delta\mathrm{MTF(syst)}_n$ are the individual systematic errors.

Most errors from a given source will have a systematic and a random component, although one usually predominates. If the effect of a given source of error is evaluated by making a large number of measurements, then the systematic component appears as a fixed offset of the mean value from the ideal value, whilst the random component appears as a random distribution about this mean. Mechanical errors in the bench system tend to produce predominantly systematic errors, whilst electronic noise in the signal from the image analyser tends to produce mainly random errors.



a) Use of rotary table

b) Use of gimbal-mounted lens

Key

A Analyser slit on centre of rotation
Q "Audit" lens in a gimbal mount
B Rotation axis of "camera" bench
O Field slide
S Rotary table
M Image analyser
P "Audit" lens
G Gimbal axis

Figure 8 - Testing image analyser off-axis

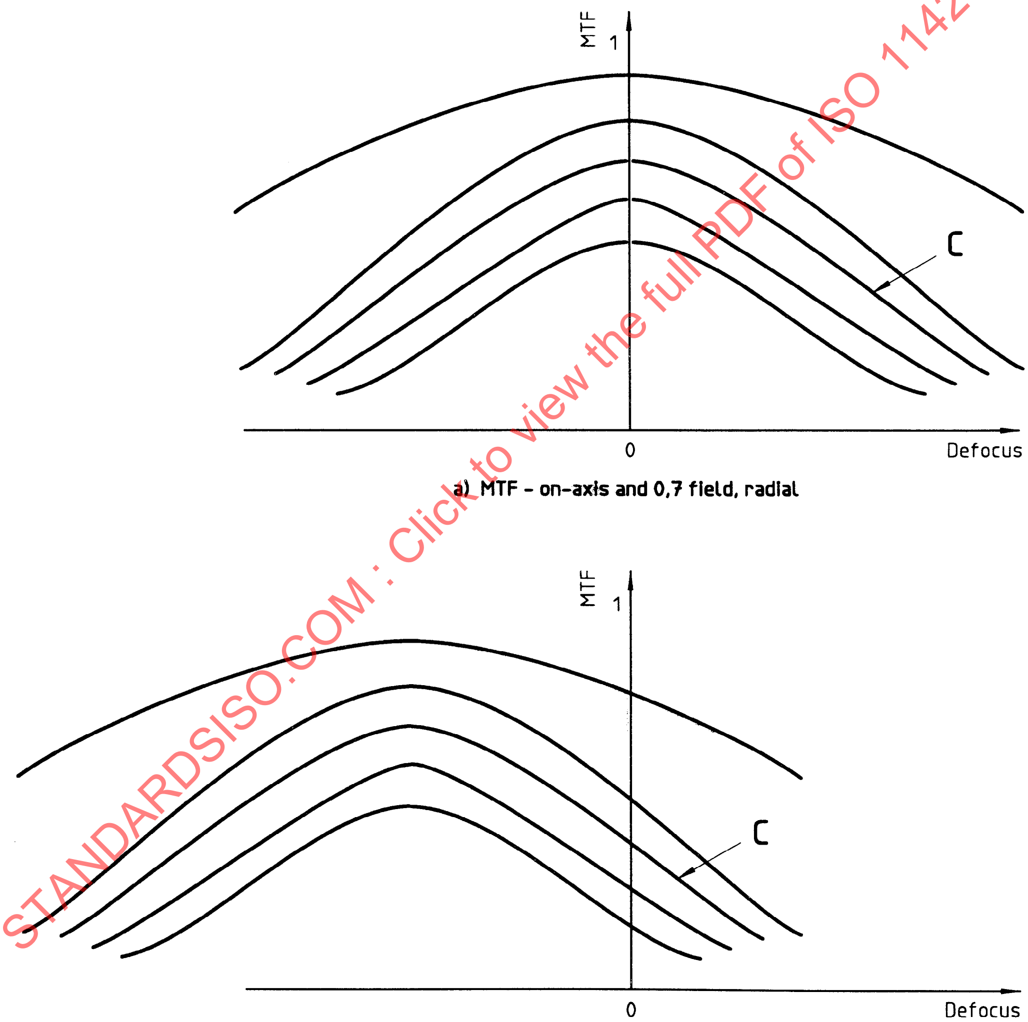
7 SPECIFYING A GENERAL EQUIPMENT ACCURACY

In instances where an accuracy figure or performance index is required which is to be descriptive of measuring equipment rather than a particular MTF measurement (for instance when establishing acceptance criteria for an equipment), one or more of the following procedures is recommended.

7.1 NOMINAL ACCURACY VALUE (NAV)

A nominal accuracy value (NAV) is generated using measured values for equipment parameters and theoretical values for lens performance. The equipment parameters to be used in this computation are those which give rise to measurement error and are selected from the list below. The theoretical values for lens performance are those given in table 1. They are in fact the rate of change of MTF with image focus [$m'(r,h')$] and the rate of change of MTF with spatial frequency [$n'(r,h')$]. The values are for a lens with a diffraction-limited performance and the particular wavelength, aperture and spatial frequency specified in the table. For the on-axis position (h'= 0) in both the radial and tangential azimuths and in the off-axis position ($h' = 0{,}7h'_{max}$) for the radial azimuth only, the values are those that apply at the focus position giving peak MTF [see figure 9 a)]. For the off-axis position ($h' = 0{,}7h'_{max}$) in the tangential azimuth a defocus arising from field curvature has been assumed, so that the values are those corresponding to the focus position where the MTF at the specified spatial frequency has dropped to 0,5 of its peak value [see figure 9 b)].

Table 1 also specifies a value for the maximum image diagonal (h'_{max}) to be used in calculating errors.



a) MTF - on-axis and 0,7 field, radial

b) MTF - 0,7 field, tangential

Key

C Given spatial frequency

Figure 9 - Through-focus diffraction-limited MTF curves as specified for generating NAV

An example calculation of NAV is found in annex C.

Table 1 provides a selection of preferred values of the relevant parameters for several typical applications. When quoting nominal accuracy figures, the chosen values for the following main parameters shall be quoted:

* *f*/number and focal length of lens
* wavelength
* full field
* conjugates
* specified spatial frequency

Table 1 - Preferred parameter values for calculating NAV

Lens type	λ µm	h'_{max} mm x 0,7	*f*/number	Spatial frequency c/mm	$m'(r, h')$ mm^{-1}			$n'(r, h')$			MTF (r, h')		
					$h' = 0$	$h' = 0$		$h' = 0$	$h' = 0,7$		$h' = 0$	$h' = 0,7$	
					R and T	R	T	R and T	R	T	R and T	R	T
Photo-graphic camera	0,4-0,7	20	2	40	5	5	18	1,3	1,3	19	0,95	0,95	0,47
				80	9	9	37	1,3	1,3	8,7	0,89	0,89	0,45
			4	40	2	2	9	2,5	2,5	16,8	0,89	0,89	0,45
				80	4	4	15	2,5	2,5	7	0,78	0,78	0,39
Mid IR Camera	3-5	10	2	16	1,6	1,6	6,6	10	10	34	0,84	0,84	0,42
				32	3,5	3,5	8,6	9,8	9,8	13,6	0,68	0,68	0,34
			4	16	1	1	2,2	19,4	19,4	23,9	0,68	0,68	0,34
				32	1	1	1,5	17	17	6,4	0,38	0,38	0,19
Far IR Camera	8-12	10	1	10	2	2	9	12,6	12,6	57	0,87	0,87	0,44
				20	4,4	4,4	13	12,4	12,4	24,6	0,75	0,75	0,37
			2	10	1	1	3,3	24,6	24,6	41	0,75	0,75	0,37
				20	1,6	1,6	3,2	22,7	22,7	13,7	0,50	0,50	0,25

NOTE - R - radial, T - tangential

The sources of error which are to be included in the calculation of NAV are as follows:

* Geometry of optical bench system (see 4.1)
* Azimuth changing (see 4.2)
* Alignment (orientation) of TTU and image analyser (see 4.3)
* Correction factors (see 4.4)
* Focus error (see 4.5)

* Spatial frequency errors (see 4.6)

* Residual aberrations in relay optics (see 4.7)

* Angular response characteristics of image analyser (see 4.10)

* Equipment signal processing (see 4.12)

7.2 STANDARD-LENS MEASUREMENTS (SLM)

The standard lens(es) most appropriate to the particular equipment application should be used.

The maximum difference between the average of several (minimum 8) MTF measurements and the theoretical MTF of an appropriate standard test lens shall be quoted, together with the maximum value of the standard deviation associated with these measurements. The values quoted shall be for each of the test conditions specified for the particular standard lens. The lens designation and the test conditions used shall be quoted with the results.

7.3 AUDIT-LENS MEASUREMENTS (ALM)

Audit lenses appropriate to the use of the equipment should be used for the assessment of ALM (a specially constructed version of the lens(es) which will be tested on the equipment would constitute a suitable audit lens).

The maximum difference between the average of several (minimum 8) MTF measurements and the "accepted" MTF of the audit lens shall be quoted, together with the maximum value of the standard deviation associated with these measurements. The values quoted shall be for appropriate specified test conditions. The test conditions should include measurements at full aperture, on-axis and at 0,7 of full field in both the radial and tangential azimuths. The lens designation and the test conditions used shall be quoted with the results.

7.4 SLIT APERTURE TEST (SAT)

As indicated earlier in 5.6, where an instrument is designed primarily for making OTF/MTF measurements of imaging systems which generate an image on a screen (e.g. image intensifier tubes and all systems producing an image on a CRT display), it is appropriate to use precision slit apertures as a means of assessing the performance of the instrument.

The suitably illuminated aperture replaces the image which would be the normal input for the OTF/MTF instrument and the measured OTF should be the Fourier transform of the slit.

Measurements should be made using a minimum of two slits. The width of one slit should be chosen to have a first zero in MTF at a spatial frequency just short of the maximum spatial frequency normally accommodated by the instrument. The width of the other should be approximately twice that of the first.

The maximum difference between the average of several (minimum 8) MTF measurements and the theoretical MTF (5.6 gives the equation for the MTF of a slit) of each slit, shall be quoted, together with the maximum value of the standard deviation associated with these measurements.

In addition to this, the difference between the average value of the spatial frequency at which the first MTF zero occurs and its theoretical value, shall be quoted as a percentage of the theoretical value.

8 ROUTINE PERFORMANCE EVALUATION

Routine evaluation of equipment is recommended to ensure that levels of accuracy are maintained. For this purpose a suitable set of audit lenses (or slits where these are more appropriate) should be used. As suggested in 7.3, the audit lenses should be special versions of the lenses most tested on the equipment, kept and maintained for this purpose.

The test conditions etc. used for such evaluations should be as specified in 7.3 (or for slits 7.4). A record of results should be kept and should include an analysis of trends. This analysis should aim to establish the sources of any deterioration in accuracy, so that faults may be rectified.

ANNEX A
(NORMATIVE)

ACCURACY OF PTF MEASUREMENT

A.1 SOURCES OF INACCURACY IN MEASURING EQUIPMENT

Although many equipments are able to measure the PTF as well as the MTF, the former is only very infrequently included in a criterion of performance and is therefore dealt with only very briefly in this International Standard.

In general, the factors which cause errors in the MTF are also potential causes of error in the PTF. The main exceptions are slit-width errors (see 4.4.1) and errors in the alignment of TTU and image analyser (see 4.3) which will normally not introduce errors into the PTF.

The equations given in the main body of the standard for calculating MTF errors may also be applied to calculating PTF errors by replacing the rate of change of MTF with the particular variable under consideration by the rate of change of PTF with that variable. A.2 describes some measurements which can be used to evaluate the general accuracy with which an equipment measures PTF.

A.2 METHODS OF EVALUATING ACCURACY OF MEASUREMENT

A.2.1 Lateral displacement of image plane origin

A lateral displacement of the position (in the image plane) taken as the origin for the purposes of determining the PTF, will add a phase term which varies linearly with spatial frequency. A displacement of x mm will produce a phase term:

$$\text{PTF(r)} = x \cdot r \cdot 2 \cdot \pi \text{ rad} = x \cdot r \cdot 360 \text{ deg}$$

This relationship can be used for assessing the PTF measuring facility on an equipment. The procedure is to set up a lens or other test piece on the equipment and make two measurements of OTF with a small accurately measured displacement x of the origin between the two (usually achieved by moving the image analyser). The difference between the two PTF curves should be in agreement with the curve predicted by the above equation.

In many equipments the linear variation of PTF with spatial frequency is automatically removed. Unless this facility can be by-passed the technique described here cannot be used.

A.2.2 Slit aperture test

The use of slit apertures for assessing the accuracy of MTF measurement is described in 5.6 and 7.4. Slits may also be used to test PTF accuracy under the same conditions.

With such a target the PTF will be zero over the spatial frequency ranges 0 to $\frac{1}{g}$ and will be π radians (180°) for the range $\frac{1}{g}$ to $\frac{2}{g}$ where g is the width of the slit.

A.2.3 Standard and audit lenses

The use of standard and audit lenses for evaluating the accuracy of MTF measurement is described in 5.6, 7.2 and 7.3. Such lenses may also be used for evaluating the accuracy of PTF measurement.

The standard lens referred to in 7.2 is used with a special aperture stop when assessing the accuracy of PTF measurement.