



BSI Standards Publication

Optics and photonics — Uncertainty of optical transfer function (OTF) measurement

National foreword

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**International
Standard**

ISO 11421

**Optics and photonics — Uncertainty
of optical transfer function (OTF)
measurement**

*Optique et photonique — Incertitude de mesure de la fonction
de transfert optique (OTF)*

**Second edition
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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document 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 11421:1997), which has been technically revised.

The main changes are as follows:

- sagittal and tangential OTF were defined;
- symbols, formulae and nomenclature have been revised
- off-axis magnification errors due to image distortion using grating objects has been newly added;
- the document has been revised to be in agreement with the terms and definitions of ISO/IEC Guide 98 (GUM) and ISO/IEC Guide 99 (VIM) regarding the expression of measurement uncertainties;
- Explanations for the calculation of measurement uncertainties have been added;
- [Annex C](#) was revised.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 (all parts), 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 uncertainty 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 uncertainty of OTF measuring equipment and for estimating the uncertainty in measurements made on specific imaging systems.

The present document lists the main sources of uncertainty 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 uncertainty in any measurement of OTF. One of the aims in preparing this document 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 uncertainty of OTF test equipment which recognize the fact that the uncertainty of a particular measurement is a function of both the equipment and the test piece.

Optics and photonics — Uncertainty of optical transfer function (OTF) measurement

1 Scope

This document 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 uncertainty for a specific measuring equipment, as well as recommending methods of routine assessment.

The main body of this document 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 references

There are no normative references in this document.

3 Terms, definitions and symbols

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 Terms and definitions

3.1.1

standard lens

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

Note 1 to entry: In order to achieve this uncertainty, 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 piano-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 uncertainty 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)

3.1.3

sagittal OTF

test pattern which is constant (shows no periodic variation) in the direction parallel to a line through the centre of the image circle

Note 1 to entry: A fixed and defined azimuthal orientation of the sample under test is required for the terms sagittal OTF and tangential OTF to be unambiguous.

Note 2 to entry: See also ISO 9334^[6] and [Figure 1](#). An illustration can also be found in Reference [\[9\]](#).

Note 3 to entry: In literature, the term “sagittal” is used synonymous with “radial”.

3.1.4

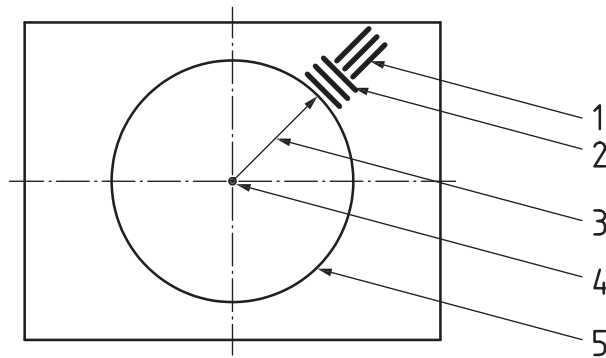
tangential OTF

test pattern which is constant (shows no periodic variation) in the direction parallel to a tangent of the image circle

Note 1 to entry: A fixed and defined azimuthal orientation of the sample under test is required for the terms sagittal OTF and tangential OTF to be unambiguous.

Note 2 to entry: See also ISO 9334^[6] and [Figure 1](#). An illustration can also be found in Reference [\[9\]](#).

Note 3 to entry: In literature, the term tangential is employed synonymous with “meridional.”



Key

- 1 sagittal to image circle
- 2 tangential to image circle
- 3 image pattern vector
- 4 center of image field
- 5 image circle

Figure 1 — Sagittal and tangential OTF, excerpt from ISO 9334:2012, Figure 1

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 distance	mm
l'	image distance	mm
Δl	error in object distance, is indexed to distinguish error sources	mm

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

Symbol	Meaning	Unit
$\Delta l'$	error in image distance, is indexed to distinguish error sources	mm
P_f	best focus point	mm
$\Delta \alpha$	angular departure of object slide from perpendicularity to reference axis	rad
$\Delta \alpha'$	angular departure of image slide from perpendicularity to reference axis	rad
i_l, i_l'	Auxiliary distance describing intermediate object distance or intermediate image distance.	mm
M	magnification	dimensionless
r	spatial frequency	mm ⁻¹ , mrad ⁻¹ , degree ⁻¹
Δr	error in spatial frequency	mm ⁻¹ , mrad ⁻¹ , degree ⁻¹
$m(r, l, h)$	rate of change of MTF with object distance	mm ⁻¹
$m'(r, l', h')$	rate of change of MTF with image distance	mm ⁻¹
$p(r, l, h)$	rate of change of MTF with object height	mm ⁻¹
$p'(r, l', h')$ or $p'(r, l', \omega)$	rate of change of MTF with image height	mm ⁻¹ , mrad ⁻¹ , degree ⁻¹
ω	field angle	mrad, degree
$\Delta \omega$	error in field angle	mrad, degree
f_c	focal length of collimator	mm
f_s	focal length of sample under test	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_0	spatial frequency for zero field angle	mm ⁻¹ , mrad ⁻¹ , degree ⁻¹
$n'(r, l', h')$	rate of change of MTF with spatial frequency	mm, mrad, degree
$\Delta MTF(r)$	error in MTF, is indexed to distinguish error sources	dimensionless
$\Delta MTF_C(r)$	MTF error of the relay lens	dimensionless
$\Delta MTF_{rl}(r)$	MTF errors resulting from aberrations of relay lens error	dimensionless

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

4 Sources of uncertainty in measuring equipment

4.1 General

In this clause the main sources of uncertainty in OTF measuring equipment are listed and the effects on a measurement of MTF are described (brief comments on the measurement of PTF is found in [Annex A](#)). This clause does not establish a GUM^[4] (Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98) conform uncertainty budget, but is treating common measurement errors. To establish a measurement uncertainty, the probability density functions of the respective measurement errors need to be identified. The measurement uncertainty is then established based on the probability density function. Usually, an expectation value of the measurand with an assigned standard uncertainty of the measurand is reported. In case of an expanded uncertainty, also a coverage interval is defined (expressed by the coverage factor k_p

see VIM[5] ISO/IEC Guide 99). The examples of common measurement errors reported in this section form the basis for a detailed analysis in terms of measurement uncertainty.

NOTE In the current revision of this document the term “accuracy” has been replaced by “uncertainty” or “error” in many sections of the text to use ISO/IEC Guide 98 (GUM) and ISO/IEC Guide 99 (VIM) conform vocabulary.

4.2 Geometry of optical bench system

4.2.1 General

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[6]). 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 document, the user shall make his own assessment of errors). For the arrangements recommended in ISO 9335, the main sources of uncertainty and the resulting MTF errors are as follows.

4.2.2 Finite object and image distance

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

Departures from straightness and perpendicularity produce departures from the ideal object and image distance, as given by [Formulae \(1\)](#) and [\(2\)](#):

$$\Delta l_{\text{str}}(h) = \Delta l_{\text{axis}}(h) + h \cdot \Delta a \quad (1)$$

for the TTU and

$$\Delta l'_{\text{str}}(h') = \Delta l'_{\text{axis}}(h') + h' \cdot \Delta a' \quad (2)$$

for the image analyser, where h and h' are object and image heights, Δl_{axis} and $\Delta l'_{\text{axis}}$ are departures from straightness of the object and image slideways 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 as image distance error is given by [Formula \(3\)](#):

$$\Delta l'(h') = \Delta l'_{\text{str}}(h') + M^2 \cdot \Delta l_{\text{str}}\left(\frac{h'}{M}\right) \quad (3)$$

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

If $m'(r, l', h')$ is the rate of change of $MTF(r)$ with image distance, then the error in MTF is given by [Formula \(4\)](#):

$$\Delta MTF(r) = m'(r, l', h') \cdot \Delta l'(h') \quad (4)$$

Further possible sources of error are in the error with which the image height h' is set and the error with which the object height h is set. The error in MTF is in this case given by [Formula \(5\)](#) (assuming image height and object height are the parameters set):

$$\Delta MTF(r) = p'(r, l', h') \cdot \Delta h' + p(r, l, h) \cdot \Delta h \quad (5)$$

where $\Delta h'$ and Δh are the errors in image height and object height respectively and p' and p are the corresponding rates of change in MTF. Usually, p' and p are small in comparison to the rate of change with image and object distance m' and m and this source of error may be ignored.

4.2.3 Infinite object distance and finite image distance

Similar considerations as for [4.2.2](#) apply except that there is only a single slideway for the image analyser. Departures from the ideal object and image distance are given in this instance by [Formulae \(6\)](#) and [\(7\)](#):

$$\Delta l_{\text{str}}(h) = 0 \quad (6)$$

$$\Delta l'_{\text{str}}(h') = \Delta l'_{\text{axis}} + h' \cdot \Delta \alpha' \quad (7)$$

and the corresponding error in MTF is given once again by [Formula \(4\)](#):

$$\Delta MTF(r) = m'(r, l', h') \cdot \Delta l'(h')$$

Errors may also arise from errors in setting image height or field angle (whichever is used in defining the I-state). These give MTF errors as previously, i.e. as per [Formula \(8\)](#):

$$\Delta MTF(r) = p'(r, l', h') \cdot \Delta h' \quad (8)$$

or, if field angle rather than image height is specified in [Formula \(9\)](#):

$$\Delta MTF(r) = p'(r, l', \omega) \cdot \Delta \omega \quad (9)$$

An error may also result from collimation errors as given by [Formula \(10\)](#) (see [5.3](#) for details):

$$\Delta MTF(r) = m(r, l', h') \cdot \Delta l'_{\text{ce}}(h) \quad (10)$$

In the above equations $h, h', \Delta l, \Delta l', p$ and p' are as defined in [4.2.2](#), ω is the field angle and $\Delta \omega$ is the error in the field angle, $m(r, l', h')$ is the rate of change of the MTF with image distance. The value of $\Delta l'_{\text{ce}}$ shall be determined from the known error Δl_{ce} in object distance. The relevant equation is copied from [5.3](#) and given by [Formula \(11\)](#):

$$\Delta l'_{\text{ce}} \approx \frac{f_s^2}{f_c^2} \Delta l_{\text{ce}} \quad (11)$$

where f_c is the focal length of the collimator and f_s is the focal length of the sample under test.

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

4.2.4 Infinite object and image distance

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 [Formula \(4\)](#):

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

Where the error in image distance $\Delta l'(h')$ is caused by this mechanical error, and $m'(r, l', h')$ is the rate of change of MTF with image distance.

Errors may also arise from errors in setting image height or field angle (whichever is used in defining the I-state). These give MTF errors as previously, i.e. as per [Formula \(12\)](#):

$$\Delta \text{MTF}(r) = p'(r, l', h') \cdot \Delta h' \quad (12)$$

or, if field angle rather than image height is specified in [Formula \(13\)](#):

$$\Delta \text{MTF}(r) = p'(r, l', \omega) \cdot \Delta \omega \quad (13)$$

An error may also result from collimation errors (see [5.3](#) for details) as described in [4.2.3](#) for a pair of collimator and sample under test. In the case of infinite object and image distance it needs to be considered, that the first pair of collimator and sample is followed by a second pair of a collimating and decollimating optic.

4.2.5 Suppression of image distance errors by refocusing

For certain types of systems (e.g. image intensifiers) an accepted test procedure involves refocusing of the sample under test for each position h' in the image field. This eliminates the image distance error $\Delta l'(h')$ caused by misalignments as discussed in [4.2.2](#), [4.2.3](#) and [4.2.4](#).

MTF errors still arise from errors in the object height Δh or errors in the image height $\Delta h'$ as described in [4.2.2](#) in [Formula \(5\)](#).

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

where $\Delta h'$ and Δh are the errors in image height and object height respectively and p' and p are the corresponding rates of change in MTF.

4.2.6 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 introduces 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 [4.2.2](#)).

4.3 Azimuth changing

4.3.1 General

With most OTF equipment 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 (which is the optical axis). This produces an object distance and/or image distance change:

$$\Delta l(\psi) \text{ and } \Delta l'(\psi)$$

for the TTU and image analyser respectively, where ψ is the azimuth angle. The MTF error resulting from this distance change is given in 4.3.2 to 4.3.4 for each of the bench configurations.

4.3.2 Finite object and image distance

The MTF error for finite object and image distance is expressed by [Formula \(14\)](#):

$$\Delta \text{MTF}(r) = m'(r, l', h') \left[\Delta l'(\psi) + M^2 \cdot \Delta l(\psi) \right] \quad (14)$$

4.3.3 Infinite object distance and finite image distance

The MTF error for infinite object and finite image distance is expressed by [Formula \(15\)](#):

$$\Delta \text{MTF}(r) = m'(r, l', h') \left[\Delta l'(\psi) + R^2 \cdot \Delta l(\psi) \right] \quad (15)$$

where R is the ratio $R = \frac{f_s}{f_c}$, with f_s test lens focal length and f_c collimator focal length.

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

4.3.4 Infinite object and image distance

The MTF error for infinite object and infinite image distance is expressed by [Formula \(16\)](#):

$$\Delta \text{MTF}(r) = m'(r, l', h') \left[\Delta l'(\psi) + (M_T \cdot R)^2 \Delta l(\psi) \right] \quad (16)$$

where R is the ratio $\frac{f_{dc}}{f_c}$, with f_{dc} decollimator focal length, f_c collimator focal length, and M_T is the magnification $\frac{f_s}{f_{cs}}$ of the test specimen (see ISO 9335:2025, Figure 4), with f_s test lens focal length and f_{cs} test lens collimator focal length.

4.3.5 Suppression of image distance errors by refocusing

If a test procedure is used where the test specimen is refocused for every test azimuth ψ (see also 4.2.5) then no image distance errors will result from a change in azimuth.

4.4 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](#)) results in an effective increase in width of the slit, given by [Formula \(17\)](#):

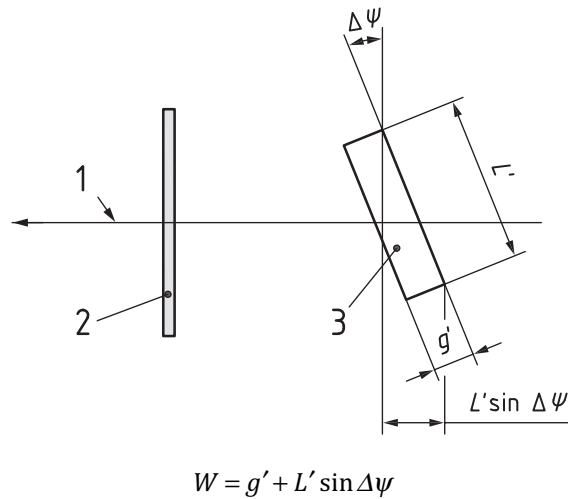
$$\Delta g' = L' \cdot \Delta\psi \quad (17)$$

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 [Formula \(18\)](#):

$$\Delta \text{MTF}(r) = \pi \cdot r \cdot L' \cdot \Delta\psi \cdot \text{MTF}(r) \cdot \left[\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{\tan(\pi \cdot r \cdot g')} \right] \quad (18)$$

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 usually result from any errors in the relative orientation of the slit and grating. The user shall make his own assessment of the effect of such errors (see [4.6](#) for the effect of spatial frequency errors on MTF).



Key

1 LSF	line spread function
2	image analyser slit
3	TTU mask/slit
L'	length of slit
g'	width of slit
$\Delta\psi$	angular misalignment
W	effective slit width

Figure 2 — Errors from alignment of analysing slit with respect to object pattern

4.5 Correction factors

4.5.1 General

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 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 factors.

4.5.2 Slit width errors

Errors or uncertainties in the widths of slits introduce errors in the measured MTF, given by [Formula \(19\)](#):

$$\Delta \text{MTF}(r) = \pi \cdot r \cdot \text{MTF}(r) \cdot \left(\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{\tan(\pi \cdot r \cdot g')} \right) \cdot \Delta g' \quad (19)$$

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

4.5.3 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. Therefore, any errors in the value of MTF of such relay lenses introduce errors into the final MTF value for the system under test. If the error in the MTF of such a relay lens is $\Delta \text{MTF}_c(r)$ and the actual value of its MTF is $\text{MTF}_c(r)$, then the error in the MTF of the test system is given by [Formula \(20\)](#):

$$\Delta \text{MTF}(r) = \text{MTF}(r) \cdot \frac{\Delta \text{MTF}_c(r)}{\text{MTF}_c(r)} \quad (20)$$

where $\text{MTF}(r)$ is the MTF of the system.

The MTF has values in the interval $[0,1]$, when the MTF value approaches $\text{MTF}_c(r) \rightarrow 0$ the signal to noise ratio decreases and the result of the above formula is dominated by noise. Therefore, the noise level and the required uncertainty need to be considered when checking if $\text{MTF}_c(r)$ is big enough.

The above relation remains valid and useful if and only if the MTF of the relay lens $\text{MTF}_c(r) \gg 0$ for the whole range of frequencies $0 \leq r \leq r_{\max}$, over which the measurement is made. The condition for $\text{MTF}_c(r)$ being great enough depends on the noise level and requires custom consideration.

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

4.5.4 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:

$$r = r_0 \cdot \cos^2(\omega) \text{ for the tangential azimuth and}$$

$$r = r_0 \cdot \cos(\omega) \text{ for the sagittal azimuth, where } r \text{ is the on-axis frequency.}$$

Errors in the value of r are produced by errors in the value of ω the field angle. The values of these errors are given by [Formula \(21\)](#):

$$\Delta r = 2 \cdot r_0 \cdot \sin(\omega) \cdot \cos(\omega) \cdot \Delta \omega \quad (21)$$

and [Formula \(22\)](#):

$$\Delta r = 2 \cdot r_0 \cdot \sin(\omega) \cdot \Delta \omega \quad (22)$$

The effect of such errors on the MTF can be calculated in the manner indicated in [4.7](#).