
**Optics and photonics — Optical
transfer function — Application —**

**Part 3:
Telescopes**

*Optique et instruments d'optique — Fonction de transfert optique —
Application —*

Partie 3: Télescopes



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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 documents 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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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 4, *Telescopic systems*.

This second edition cancels and replaces the first edition (ISO 9336-3:1994), which has been technically revised.

The main changes compared to the previous edition are as follows:

- update of the document based on the latest technical developments;
- [Annex A](#) regarding tests on components and sub-assemblies using azimuth scanning systems removed, due to lack of practical relevance;
- two new Annexes added regarding test methods using detector arrays and deriving an objective image quality criterion from the MTF.

A list of all parts in the ISO 9336 series can be found on the ISO website.

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

Methods of assessing the imaging quality of telescopic systems can be found in ISO 14490-7. The methods described in this document are basically subjective, relying as they do on the judgement of the observer and the quality of his vision. The technique of measuring the “limit of resolution” is relatively easy and quick to perform and provides a single figure of merit for each orientation of the test pattern. However, being a subjective measurement, it can be open to significant variations in its results. Measuring the optical transfer function (OTF), or more usually just its modulus, the modulation transfer function (MTF), provides a completely objective means of evaluating imaging quality that can be compared directly with the theoretical assessment done by the optical system designer.

Integration of the system MTF over a certain domain of spatial frequencies and normalised to the diffraction limited MTF will provide a single figure of merit that is a reasonable representation of the system performance without relying on any subjective assessment. When the spatial frequency domain is selected in accordance with the properties of the detector system the method can be applied to telescopic systems operating with any detector type, thus not limiting the method to visual observation. This is of importance as in state-of-the-art telescopes the same optical path can be used for visual observation as well as for wavelengths outside the visual range (using appropriate detector systems).

As a special case, an “objective limit of resolution”, providing a single figure of merit, can be derived from a measurement of MTF by using the latter in combination with a “contrast sensitivity” curve for the eye and a measurement of MTF may also be used as the basis for several other image quality criteria (see [Annex B](#)).

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Optics and photonics — Optical transfer function — Application —

Part 3: Telescopes

1 Scope

This document specifies a method of testing telescopes in terms of imaging states aimed at making valid optical transfer function (OTF) measurements.

This document includes two annexes ([Annex A](#) and [B](#)) that provide information on the more recent techniques for measuring optical transfer function and methods of deriving image quality criteria from such measurements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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*

ISO 9335, *Optics and photonics — Optical transfer function — Principles and procedures of measurement*

ISO 14132-1, *Optics and photonics — Vocabulary for telescopic systems — Part 1: General terms and alphabetical indexes of terms in ISO 14132*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 9334 and ISO 14132-1 apply.

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

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

4 General description of test specimen types and the relevance of OTF tests

The specimens considered are telescopic observational instruments with direct view used for viewing remote objects and include many instruments such as telescopes, binoculars, telescopic sights or spotting scopes.

Ideally, instruments would be best with no astigmatism and no field curvature coupled with good chromatic correction but frequently compromises as mentioned above shall be tolerated.

Many optical systems include roof prisms to give a compact instrument. However, the image produced by such systems is basically made up of two superimposed images and the accuracy with which they match will depend on the accuracy with which the roof edge has been constructed. In such cases the orientation of the roof edge shall be noted (see [5.5](#)).

In use, the eye is coherently coupled to the telescope, so it may be contended that the only valid test would be one that included the eye: reference is made to the case of cascaded optical systems in the introduction to ISO 9334. However, in observer tests using telescopes, improved performance has been obtained with instruments with better measured OTF performance in a variety of tests, including contrast sensitivity using sinusoidal grating targets, which confirms the value of OTF tests.

OTF tests also enable performance to be compared with that computed by the telescope designer and provide effective quality assurance tests of production specimens.

When considering the details of tests, some features of the eye need to be borne in mind, especially its ability to accommodate for varying object distances and to adjust the working aperture, varying the iris size, according to the ambient illumination. Thus firstly, unlike the photographic lens testing case, refocusing for off-axis tests is necessary. Secondly, the working aperture of the telescope, i.e. the exit pupil diameter, will need to match the receiving eye pupil, which generally has a range of 7 mm down to 2 mm diameter for different ambient illumination levels. The size of the evaluation pupil for the MTF measurement (receiving pupil in the test setup) is specified in the corresponding imaging state tables.

5 Test arrangement

5.1 General

MTF values can typically be obtained by

- a) direct measurement of frequency response to targets of different spatial frequencies,
- b) calculating from measurements of wavefront aberration in the exit pupil,
- c) calculating from measurement of the intensity distribution generated through the system under test of a (quasi-ideal) point source.

Cases b) and c) obtain two-dimensional MTFs from which one-dimensional MTFs may be deduced.

5.2 Arrangement of optical bench

For case 5.1 a) direct measurement of the frequency response to targets of different spatial frequencies, a typical test setup is shown schematically in Figure 1. The separation between the test pattern unit and the collimator is adjusted to give an infinite conjugate for the test. The separation between the image analyser collimator ("decollimator") and the image analyser needs to be adjustable by a suitable micrometer, operating on the image analyser focus slideway, to position the image analyser at the image of the test pattern.

When the object generator assembly (test pattern unit and collimator) and the image analyser assembly (image analyser collimator and image analyser) are aligned, without the optical system to be tested, the micrometer setting for optimum response of the test system will be the datum. When the optical system to be tested is positioned for an on-axis test, refocusing of the image analyser is needed and any change from the datum setting gives a measure of the on-axis diopetre setting of the system being tested. In off-axis tests, a different setting from that for on-axis tests will be found and the new change from the datum will give the diopetre setting for the particular field point and azimuth of the test; the difference from that of the on-axis test gives a measure of the field curvature.

In off-axis tests with an arrangement where the test specimen is retained in a fixed position, the object generator assembly will be rotated about a point on the reference axis, at or near the entrance pupil of the specimen, through an angle ω_p . The image analyser assembly will be rotated about a point on the reference axis, at or near the exit pupil of the specimen, through an angle ω'_p .

Descriptions of optical bench arrangements for testing a variety of different types of telescopic system can be found in References [1] and [2].

5.3 Collimators

The object collimator shall be a well-corrected achromat with a focal length at least twice that of the objective of the specimen and a working aperture diameter at least 10 mm greater than the objective of the specimen. Reflective (off-axis) or catadioptric collimators may be preferred, especially for tests at different wavelengths, thus providing a constant apparent test object distance without the requirement for refocusing when changing the wavelength.

For the image analyser collimator, a convenient focal length would be 100 mm as this would ensure that the movement of the image analyser along its focus slideway would be within the range of a readily available (e.g. 25 mm) micrometer movement if the field curvature reached 2 m^{-1} . However, there may be circumstances where the resolution of the image analyser may require a longer focal length to be used. Alternatively, an image analyser collimator with fixed focal length in combination with well corrected microscope objectives of different lateral magnifications can be used.

5.4 Spectral response

Unless otherwise specified, the spectral response of the test system shall match that of an observer using the specimen in its normal viewing role or that of the detector if the specimen is intended for non-visual use (e.g. infrared systems). This may be achieved by using a specially designed filter combination to give the desired match in conjunction with the source emission and the detector spectral sensitivity (see notes to [Table 2](#)).

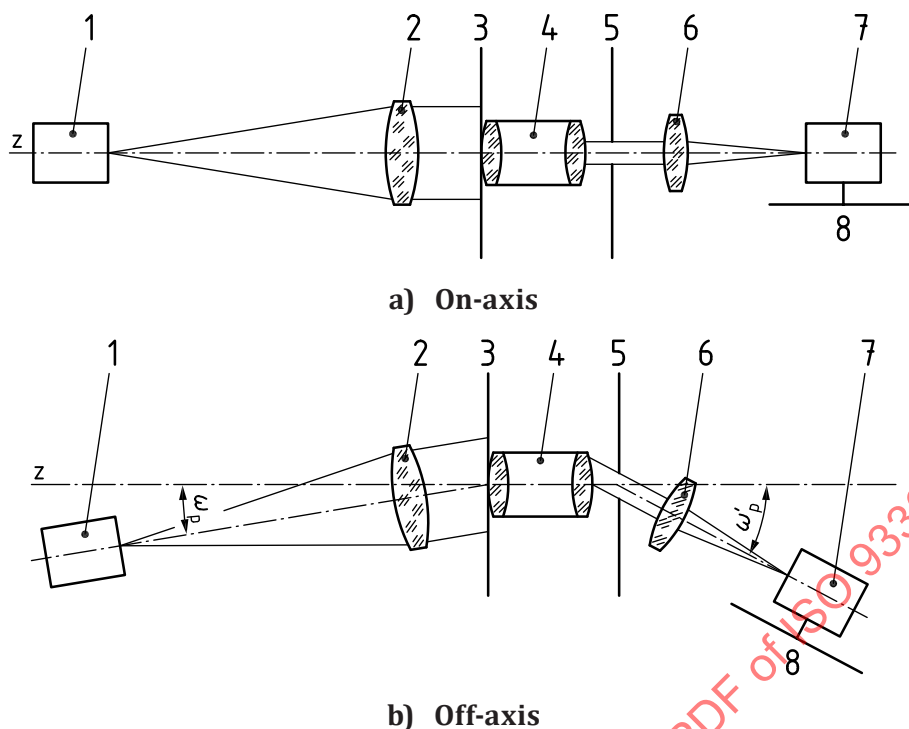
Ideally, measurements shall be carried out with narrow bandwidth (quasi-monochromatic) radiation, preferably at the dominant wavelength of the eye or the detector spectral response. If more than one wavelength or a wavelength range is of interest, it is advisable to perform quasi-monochromatic tests in succession to ensure the separation of chromatic and resolution deficiencies.

The most effective position for filters is after the image analysing element as the effect of stray radiation is reduced. However, in good laboratory conditions, it is quite practicable to position the filter within the test pattern unit.

5.5 Spatial frequency range

To a large extent, the test specimen will be the controlling influence on spatial frequency ranges as derived in object space. In image space, the range might be limited by the resolution of the eye or the detector. The lower and upper bound of the spatial frequency range shall be defined in the imaging state table.

The corresponding frequency range in object space will be given by M times the lower and upper bounds, where M is the magnification of the telescope.



Key

1	test target unit	6	image analyser collimator (decollimator)
2	object collimator	7	image analyser
3	fixture for test specimen	8	image analyser focus slideway
4	test specimen	ω_p, ω'_p	object and image pupil field angles
5	diaphragm (with role of exit pupil);	z	reference axis

Figure 1 — Schematic setup — Object at infinity, image nominally at infinity

The spatial frequency in object space may be obtained either:

- by calculation, using the linear spatial frequency of the test pattern in conjunction with the focal length of the collimator; or
- by measurement of the angular subtense of a number of cycles of the collimated test pattern, followed by the appropriate calculation to give the spatial frequency.

5.6 Azimuths

It is permissible to measure one-dimensional MTFs. These shall be taken at the azimuths with highest and lowest MTF values. For off-axis image points, this will generally be in the radial and tangential directions. In case of rotational asymmetry (e.g. for on-axis points) this fact shall be noted and measurement results given for the directions of highest and lowest MTF values.

A special case is that of systems containing roof prisms where one of the measurements shall be made with the direction of variation of intensity of the test pattern normal to the roof edge.

5.7 Preparing the test specimen

The exposed optical surfaces shall be clean and the specimen shall have attained the stable temperature of the test laboratory.

Unless otherwise specified, focusing eyepieces shall be set for an infinite conjugate ($0,0 \text{ m}^{-1}$). It is permissible to refocus for best MTF (e.g. when measurements at different off-axis positions or at different wavelengths are taken). In cases 5.1 a) and c), refocusing shall preferably be accomplished on the analyser side (Key 8 of Figure 1). For case 5.1 b), refocusing with the eyepiece (or on the objective side of the specimen) is permissible. In any case, the amount of refocusing required shall be noted in the test report.

For tests assessing performance with a reduced exit pupil, uncertainties can arise due to the difficulty of correctly positioning a stop at the exit pupil especially when making off-axis measurements. This is due to a combination of vignetting, pupil distortion and pupil wander along the reference axis relative to the on-axis pupil position. Consequently, it is preferable to position a stop of the corresponding diameter at the entrance pupil. The size of the stop is given by the product of the desired exit pupil and the magnification of the specimen.

5.8 Auxiliary equipment

In addition to fixtures for holding test specimens, some means for aligning the test beam with the input axis of the specimen can be needed particularly for instruments having large offsets between input and output axes. Mechanical means should be used for this if practical; otherwise, adjustable periscopic beam deviators using a framework and plane mirrors may be employed. The combined effect of all auxiliary equipment on the wavefront aberration shall be significantly lower than the accuracy of measurement.

6 Normalization of OTF values

The normalization arrangement with equipment which permits the response at zero cycles to be set to 1,0 will generally be satisfactory but further checks can be used if needed.

7 Test condition

The testing shall be carried out in accordance with the general principles and procedures given in ISO 9335.

8 Specification of the imaging state

8.1 Test specimen

Table 1 specifies an imaging state for the test specimen.

Table 1 — Imaging state of test specimens

Parameter	Value/Setting	Notes	Clause
configuration	in line in line with offset angled periscopic	Some configurations require auxiliary equipment.	5.8
magnification and objective diameter	example: 6×42 8×40 10×30	these examples give exit pupils of 7 mm 5 mm 3 mm	—

Table 1 (continued)

Parameter	Value/Setting	Notes	Clause
exit pupil	7 mm	To obtain reduced exit pupil diameters appropriate stops are used.	5.7
	5 mm		
	3 mm		
	2 mm		
field of view	e.g. $\pm 3^\circ$	In object space.	Clause 4
eyepiece focus setting	infinite conjugate (0 m ⁻¹)	Specify if other setting is used	5.7

8.2 Measuring equipment

[Table 2](#) specifies an imaging state for the measuring equipment.

Table 2 — Imaging state for measuring equipment

Parameter	Value/Setting	Notes	Clause
bench configuration	object at infinity cases 5.1 a) and c): image side decollimator forms an image in the plane of the image analyser wavefront sensor in exit pupil	focus adjustment is needed	5.2 and 5.3
spectral characteristics	dominant (monochromatic wavelength for nominal use)	specify source characteristics (i.e. center bandwidth)	5.4 $V(\lambda)$ = spectral luminous efficiency for photopic vision
	wavelength(s) selected for measurement	specify source characteristics (i.e. center wavelength and bandwidth)	—
	polychromatic	source: band filter and analyser combination should have overall spectral characteristics which match the $V(\lambda)$ curve of the eye	—

8.3 Measurement

[Table 3](#) specifies an imaging state for the measurement.

Table 3 — Imaging state for measurement

Parameter	Value/Setting	Notes	Clause
MTF	MTF is essential PTF (phase transfer function) if specified	—	—

Table 3 (continued)

Parameter	Value/Setting	Notes	Clause
focusing	on-axis: maximum integral MTF (specify lower and upper bound of spatial frequency)	— datum focus for infinity to be established — different focussing criteria have to be specified — focus for both radial and tangential sections can be required — off-axis: refocusing for both radial and tangential sections will be needed	—
exit pupil	full aperture and 3 mm	Other if requested as defined in Table 1 . Maximum aperture for eye related measurement shall be 7 mm.	—
pupil field angles	on-axis optional: off-axis ±0,5 semifield ±0,7 semifield ±0,85 semifield	—	—
reference angle	0°, 90°, 180° and 270° angles of roof edge	In case of rotational symmetry one angle is sufficient.	—
azimuth	radial and tangential	—	—
diopetre setting	infinite conjugate	For fixed focus specimens adjust de-collimator accordingly. Calculated from the difference between the datum focus and the on-axis focus setting. Specify how refocusing is accomplished.	—
field curvature	—	Calculated from the difference between the on-axis focus and off-axis focus setting in both radial and tangential sections for selected field angles.	—
astigmatismus	—	Calculated from the difference between radial and tangential focus settings at selected field angles.	—
reference plane	—	Object at infinity, no test specimen; image analyser focused for maximum MTF.	—
selected spatial frequencies in image space	The sampling has to be sufficient to represent the measured MTF curve. Generally 8 sampling points over the represented frequency range should be sufficient.	—	5.5

9 Presentation

The measured MTF shall be plotted together with the diffraction limited MTF in a diagram versus 10 equidistant frequencies over the practical measurement range.

10 Accuracy of equipment

The uncertainty of measurement shall be assessed either by using recognized or known test telescopes, or by estimation of all systematic and random sources of error.

One method is to replace the test specimen and image analyser collimator with a collimator, which is similar to the object collimator, to form an image of the test target without the test specimen.

Then, using a narrow bandwidth filter at 546 nm, and assuming that the collimators have diffraction limited performance, the correct response should be obtained through a range of spatial frequencies. Specify if different wavelengths are used.

Alternatively, special instruments of stable construction can be used. To facilitate the alignment of the test setup, for all field points considered, a graticule with circles is incorporated so that each field point is identified as the centre of a circle (see Reference [3]).

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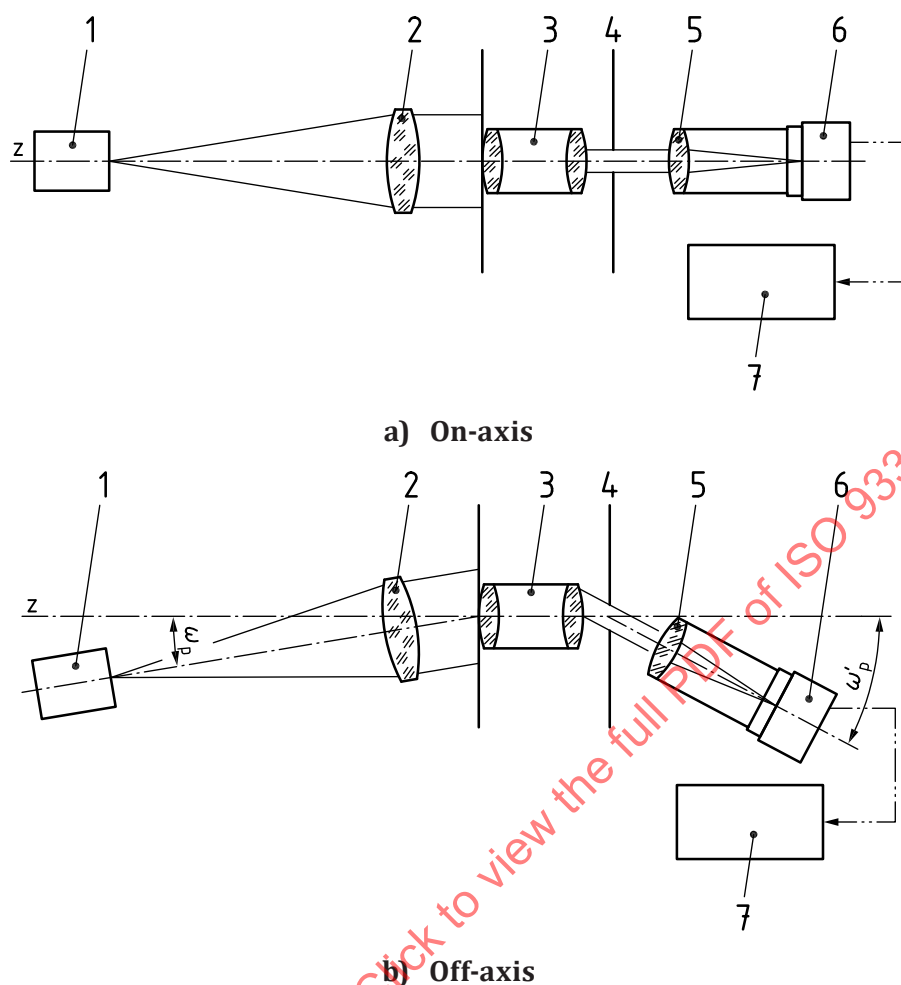
Annex A (informative)

MTF Test methods using detector arrays

A.1 Measurement technique

Digital video cameras and digital still cameras can form the basis of a convenient facility for measuring OTF, or just the MTF, of telescopic systems. [Figure A.1](#) is a diagram of such an arrangement (note similarities to [Figure 1](#)).

The test target can be of several forms, but in general the most convenient are illuminated pinholes, slits or straight edges mounted so that their orientation can be varied, or a special form of radial grating (Siemens star) where the transmission or reflectance of the grating lines varies sinusoidally perpendicular to their length. The image analyser is either a digital video camera or a digital SLR still camera, where the normal lens is in effect replaced by the decollimator or a decollimator combined with well corrected microscope objectives (see [5.3](#)). The output from the image analyser camera goes to a suitably equipped PC where its output is stored and analysed to yield the OTF/MTF.



Key

1	illuminated test target	5	image analyser collimator (decollimator)
2	collimator	6	digital camera
3	test specimen	7	computer
4	diaphragm (with role of exit pupil)	ω_p, ω'_p	object and image pupil field angles
		z	reference axis

Figure A.1 — Arrangement for measuring the MTF of a telescopic system using a digital camera

An important consideration in using a detector array as an image analyser is associated with the fact that in principle the image it generates will have aliasing (i.e. the exact image profile it generates will vary as the position of the primary image changes with respect to the array). However, when necessary, there are ways of avoiding this difficulty, most of which are described in References [2], [6] and [7]. When the test target is a slit or edge, the technique consists in orientating the slit or edge at a small angle to the rows or columns of the array so that each row or column of the array will produce a profile of the slit or edge where its position relative to a pixel of the array is different. By removing this shift from each profile and then taking their average, a profile is obtained that when further processed will yield a unique MTF. If the target has a sinusoidal profile no aliasing occurs provided the spatial frequency is limited to values below the Nyquist limit (i.e. the spatial frequency equivalent to twice the spacing between pixels of the array). The use of a straight edge, or radial gratings, for measuring the MTF of digital still cameras is described in Reference [7], which also provides information on suitable software for processing the output of the array.

Particular points to note when using one or other of these techniques are as follows:

- The measured MTF with the test piece in place shall be corrected for the MTF of the camera-subassembly (i.e. sensor and lenses). The latter can be determined by measuring the MTF with the test piece removed and with an aperture stop positioned at the decollimator with a diameter approximating the diameter of the exit pupil of the test piece. Note that the MTF of the camera shall be taken as the measured MTF corrected for the MTF of the decollimator. If we assume that the latter is diffraction limited, its MTF can be calculated from knowledge of its focal length and the diameter of the stop used for the measurement.
- The MTF of the camera may vary with the orientation of the test target so that the correction applied to a measured MTF may be different for different target orientations.
- The cameras shall be used in a mode where no non-linear or spatial frequency dependent processing occurs within the camera. For most digital still cameras this is usually satisfied by using them in RAW mode.

A.2 Typical examples of the calculations involved

A.2.1 MTF of the camera

If the detector array is square with area $A(\text{mm})^2$ and contains N megapixels, the width of each pixel p (mm) will be given by:

$$p = \sqrt{\frac{A}{N \cdot 10^6}} \quad (\text{A.1})$$

The Nyquist limit will be given by $\frac{1}{2p}$ (c/mm) and the theoretical maximum and minimum measured MTFs using an edge or slit target will be given by:

$$MTF_{\max}(s) = \frac{\sin(\pi p s)}{\pi p s} \quad (\text{A.2})$$

$$MTF_{\min}(s) = \frac{\sin(2\pi p s)}{2\pi p s} \quad (\text{A.3})$$

where s is the spatial frequency in (c/mm).

A.2.2 MTF of camera plus decollimator

If the decollimator has a focal length f , the equivalent MTF in c/mrad will be given by [Formula A.4](#) and [A.5](#):

$$MTF_{\max}(v) = \frac{\sin(\pi p v \cdot 1\,000 / f)}{\left(\pi p v \cdot \frac{1\,000}{f}\right)} \quad (\text{A.4})$$

$$MTF_{\min}(v) = \frac{\sin(2\pi p v \cdot 1\,000 / f)}{\left(2\pi p v \cdot \frac{1\,000}{f}\right)} \quad (\text{A.5})$$

where v is the spatial frequency in (c/mrad).

The Nyquist limit in c/mrad is given by $\frac{f}{2p \cdot 1\,000}$.

EXAMPLE Camera with $N = 10$ and $A = 23,6 \text{ mm} \times 15,8 \text{ mm} = 372,88 \text{ mm}^2$ used with a decollimator of focal length $f = 100 \text{ mm}$. [Formula A.1](#) to [A.5](#) yield: $p = 0,006 \text{ mm}$; Nyquist limit = $8,2 \text{ c/mrad}$; at 2 c/mrad (i.e. the approximate limit of resolution of the eye) the $MTF_{\max}(v) = 0,98$ and $MTF_{\min}(v) = 0,90$.

This would suggest that for the best accuracy it is necessary to use a sloping slit or sloping edge technique to remove the effect of aliasing. However, in practise, it is very likely that there is in fact no difference between the two, partly because of cross-talk between pixels but largely because of the blur-filters introduced into digital cameras to remove, or significantly reduce, the aliasing problem. This will of course also mean that the MTF will be less than that indicated theoretically, although it should be adequate for measurements up to the resolution limit of the eye. If necessary a longer focal length decollimator may be used in order to stretch the spatial frequency range.

A.3 Measurement using a radial grating

A radial grating pattern (Siemens star) where the luminance of the target varies sinusoidally in the tangential direction allows measurements of MTF to be made without the problems associated with aliasing (see References [2], [6] and [7]). A difficulty that arises from the use of a radial grating is that of obtaining a signal that allows the measurements to be normalised to unity at zero spatial frequency (or at a very low spatial frequency) since the diameter of the grating shall be limited.

This can be overcome by having one or more areas of the target with extra targets, providing a very low spatial frequency, which can be used for normalization purposes.

Measurements using a radial grating allow the MTF to be measured in different azimuths without the need to rotate the target and can provide the equivalent of an azimuth scanning MTF system.

Annex B (informative)

Deriving an objective image quality criterion from the MTF

B.1 General

A significant amount of research has been done on relating various objective image quality criteria to the subjective evaluation of the quality of an image produced by an optical system, including systems such as telescopic sights. One of the problems is the very different assessment of quality that different observers can make. Another difficulty is that the residual aberrations of the instrument can either add to or subtract from the aberrations of the eye, thus affecting the overall performance of the eye/instrument system. That relates particularly to systems such as telescopes where the coupling between the instrument and the observer is a coherent one.

However, there are several MTF related criteria that can be used as good objective means of assessing the relative merits of different telescopic systems as well as a means of quality control that is not subject to the variability of human judgement. One of these is the use of the MTF at a single spatial frequency. A similar type of measurement can be made using a static sinewave radial grating as described in [A.3](#). This Annex provides an indication of how three more of these criteria can be derived from a measure of the MTF.

B.2 Limit of resolution

An objective measure of the limit of resolution can be derived from the measured MTF of a telescope in combination with the reciprocal of a Contrast Sensitivity Function (CSF) curve for the eye. This is illustrated in [B.1](#). For evaluating the effect of varying the contrast of the target, a scaling factor can be applied to the MTF axis of the MTF curve, whilst for evaluating the effect of target luminance a CSF for a different luminance can be used. From the point of view of standardization the only difficulty is that at present no set of standard CSFs has been agreed, although the results of appropriate measurements have been described (see Reference [\[8\]](#)).