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Optics and photonics — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems

Optique et photonique — Fonction de transfert optique — Principes de mesure de la fonction de transfert de modulation (MTF) des systèmes de formation d'image échantillonnés

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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

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

ISO 15529 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 15529:1999) which has been technically revised to include measurement and test procedures for aliasing of sampled imaging systems.

Introduction

One of the most important criteria for describing the performance of an imaging system or device is its MTF. The conditions that must be satisfied by an imaging system for the MTF concept to apply are specified in ISO 9334. They are that the imaging system must be linear and isoplanatic.

For a system to be isoplanatic the image of a point object (i.e. the point spread function) must be independent of its position in the object plane to within a specified accuracy. There are types of imaging systems where this condition does not strictly apply. These are systems where the image is generated by sampling the intensity distribution in the object at a number of discrete points, or lines, rather than at a continuum of points.

Examples of such devices or systems are: fibre optic face plates, coherent fibre bundles, cameras that use detector arrays such as CCD arrays, line scan systems such as thermal imagers (for the direction perpendicular to the lines), etc.

If one attempts to determine the MTF of this type of system by measuring the line spread function of a static narrow line object and calculating the modulus of the Fourier transform, one finds that the resulting MTF curve depends critically on the exact position and orientation of the line object relative to the array of sampling points (see Annex A).

This International Standard specifies an “MTF” for such systems and outlines a number of suitable measurement techniques. The specified MTF satisfies the following important criteria:

— the MTF is descriptive of the quality of the system as an image-forming device;

— it has a unique value that is independent of the measuring equipment (i.e. the effect of object slit widths, etc., can be de-convolved from the measured value);

— the MTF can in principle be used to calculate the intensity distribution in the image of a given object, although the procedure does not follow the same rules as it does for a non-sampled imaging system.

This International Standard also specifies MTFs for the sub-units, or imaging stages, which make up such a system. These also satisfy the above criteria.

A very important aspect of sampled imaging systems is the “aliasing” that can be associated with them. The importance of this is that it allows spatial frequency components higher than the Nyquist frequency to be reproduced in the final image as spurious low frequency components. This gives rise to artifacts in the final image that can be considered as a form of noise. The extent to which this type of noise is objectionable will depend on the characteristics of the image being sampled. For example, images with regular patterns at spatial frequencies higher than the Nyquist frequency (e.g. the woven texture on clothing) can produce very visible fringe patterns in the final image, usually referred to as moiré fringes. These are unacceptable in most applications if they have sufficient contrast to be visible to the observer. Even in the absence of regular patterns, aliasing will produce noise-like patterns that can degrade an image.

A quantitative measure of aliasing can be obtained from MTF measurements made under specified conditions. This International Standard defines such measures and describes the conditions of measurement.

Optics and photonics — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems

1 Scope

This International Standard specifies the principal MTFs associated with a sampled imaging system, together with related terms and outlines a number of suitable techniques for measuring these MTFs. It also defines a measure for the “aliasing” related to imaging with such systems.

This International Standard is particularly relevant to electronic imaging devices such as digital still and video cameras and the detector arrays they embody.

Although a number of MTF measurement techniques are described, the intention is not to exclude other techniques, provided they measure the correct parameter and satisfy the general definitions and guidelines for MTF measurement as set out in ISO 9334 and ISO 9335. The use of a measurement of the edge spread function, rather than the line spread function (LSF), is noted in particular as an alternative starting point for determining the OTF/MTF of an imaging system.

2 Normative references

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

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

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

3 Terms and definitions and symbols

3.1 Terms and definitions

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

3.1.1
sampled imaging system
imaging system or device, where the image is generated by sampling the object at an array of discrete points, or along a set of discrete lines, rather than a continuum of points

NOTE 1 The sampling at each point is done using a finite size sampling aperture or area.

NOTE 2 For many devices “the object” is actually an image produced by a lens or other imaging system (e.g. when the device is a detector array).

3.1.2
sampling period
a
physical distance between sampling points or sampling lines

NOTE Sampling is usually by means of a uniform array of points or lines. The sampling period may be different in two orthogonal directions.

3.1.3
Nyquist limit
maximum spatial frequency of sinewave that the system can generate in the image equal to $1/(2 \cdot a)$

NOTE See also 3.1.9.

3.1.4
line spread function of the sampling aperture of a sampled imaging system
$L_{\text{ap}}(u)$
variation in sampled intensity, or signal, for a single sampling aperture or line of the sampling array, as a narrow line object is traversed across that aperture, or line and adjacent apertures or lines, where the direction of traverse is perpendicular to the length of the narrow line object and in the case of systems which sample over discrete lines, is also perpendicular to these lines

NOTE $L_{\text{ap}}(u)$ is a one-dimensional function of position u in the object plane, or equivalent position in the image.

3.1.5
optical transfer function of a sampling aperture
$D_{\text{ap}}(r)$
Fourier transform of the line spread function, $L_{\text{ap}}(u)$, of the sampling aperture

$$D_{\text{ap}}(r) = \int L_{\text{ap}}(u) \times \exp(-i \times 2\pi \times u \times r)\,\mathrm{d}u$$

where r is the spatial frequency

3.1.6
modulation transfer function of a sampling aperture
$T_{\text{ap}}(r)$
modulus of $D_{\text{ap}}(r)$

3.1.7
reconstruction function
function used to convert the output from each sampled point, aperture or line, to an intensity distribution in the image

NOTE The reconstruction function has an OTF and MTF associated with it denoted by $D_{\text{rf}}(r)$ and $T_{\text{rf}}(r)$ respectively.

3.1.8
MTF of a sampled imaging system
$T_{\text{sys}}(r)$
product of $T_{\text{ap}}(r)$ and $T_{\text{rf}}(r)$ with the MTF of any additional input device (e.g. a lens) and output device (e.g. a CRT monitor) which are regarded as part of the imaging system

NOTE When quoting a value for T_{sys} it should be made clear what constitutes the system. The system could, for example, be just a detector array and associated drive/output electronics, or could be a complete digital camera and CRT display.

3.1.9
Fourier transform of the image of a narrow slit produced by the imaging system
$F_{\text{img}}(r)$
This is given by:

$$F_{\text{img}}(r) = \int L_{\text{img}}(u) \times \exp(-i \times 2\pi \times u \times r)\, \mathrm{d}u$$

where $L_{\text{img}}(u)$ is the variation in sampled intensity, or signal, across the image of a narrow slit object generated by the complete system

NOTE $L_{\text{img}}(u)$ is different for different positions of the slit object relative to the sampling array.

3.1.10
aliasing function of a sampled imaging system
$A_{\text{F, sys}}(r)$
half the difference between the highest and lowest value of $|F_{\text{img}}(r)|$ [i.e. the modulus of $F_{\text{img}}(r)$] as the image of the MTF test slit is moved over a distance equal to, or greater than, one period of the sampling array

$$A_{\text{F, sys}}(r) = \frac{\left(\left|F_{\text{img}}(r)\right|_{\text{max}} - \left|F_{\text{img}}(r)\right|_{\text{min}}\right)}{2}$$

NOTE 1 It is the limiting value of this difference as the width of the test slit approaches zero (i.e. its Fourier transform approaches unity).

NOTE 2 $A_{\text{F, sys}}(r)$ is a measure of the degree to which the system will respond to spatial frequencies higher than the Nyquist frequency and as a result generate spurious low frequencies in the image.

3.1.11
aliasing ratio of a sampled imaging system

$A_{\text{R, sys}}(r)$
ratio $A_{\text{F, sys}}(r)/(|F_{\text{img}}(r)|)_{\text{av}}$, where $(|F_{\text{img}}(r)|)_{\text{av}}$ is the average of the highest and lowest value of $|F_{\text{img}}(r)|$ as the image of the MTF test slit is moved over a distance equal to, or greater than, one period of the sampling array

NOTE $A_{\text{R, sys}}(r)$ can be considered as a measure of the noise/signal ratio where $A_{\text{F, sys}}(r)$ is a measure of the noise component and $(|F_{\text{img}}(r)|)_{\text{av}}$ as a measure of the signal.

3.1.12
MTF of an imaging pick-up subsystem
$T_{\text{imp}}(r)$
product of $T_{\text{ap}}(r)$ with $T_{\text{lens}}(r)$, where $T_{\text{lens}}(r)$ includes the effect of any optical anti-aliasing filters that are part of the system and which form the image on the sampling array

3.1.13
aliasing potential of a sampled imaging system
$A_{\text{P, imp}}$
ratio of the area under $T_{\text{imp}}(r)$ from r = 0,5 to r = 1, to the area under the same curve from r = 0 to r = 0,5, where the spatial frequency r is normalized so that $1/a$ becomes unity

3.2 Symbols

See Table 1.

Table 1 — Symbols used

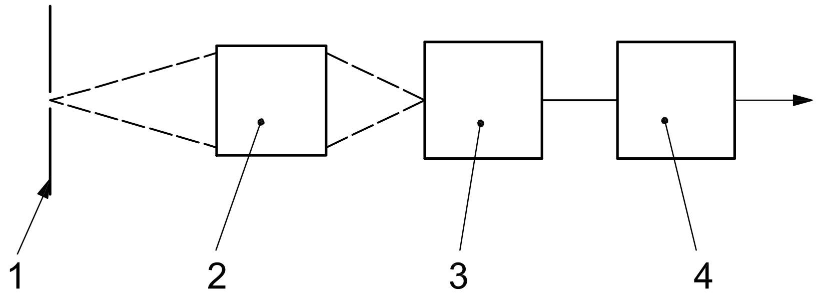
Symbol	Parameter	Units
a	sampling period	mm, mrad, degrees
$1/(2 \cdot a)$	Nyquist spatial frequency limit	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
u	local image field coordinate	mm, mrad, degrees
r	spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$L_{ap}(u)$	line spread function of a sampling aperture	1
$D_{ap}(r)$	optical transfer function of a sampling aperture	1
$T_{ap}(r)$	modulation transfer function of a sampling aperture	1
$D_{rf}(r)$	optical transfer function of the reconstruction function	1
$T_{rf}(r)$	modulation transfer function of the reconstruction function	1
$T_{sys}(r)$	modulation transfer function of a sampled imaging system	1
$T_{imp}(r)$	modulation transfer function of an imaging pick-up system	1
$F_{slt}(r)$	Fourier transform of the slit object	1
$D_{lens}(r)$	optical transfer function of the optical system including any anti-aliasing filters	1
$T_{lens}(r)$	modulation transfer function of the optical system including any anti-aliasing filters	1
$F_{img}(r)$	Fourier transform of the final image of the slit object	1
$A_{F, sys}(r)$	aliasing function of the system under test	1
$L_{in}(u)$	line spread function of the combination of slit object, relay lens and sampling aperture	1
$F_{in}(r)$	Fourier transform of $L_{in}(u)$	1
$L_{av}(u)$	line spread function obtained by averaging the LSF associated with different positions of the object slit relative to the sampling array	1
$F_{av}(r)$	Fourier transform of $L_{av}(u)$	1
$L_{img}(u)$	line spread function associated with the complete imaging system	1
$A_{R, sys}(r)$	aliasing ratio associated with the complete imaging system	1
$A_{P, imp}$	aliasing potential associated with the imaging sub-system	1

4 Theoretical relationships

4.1 Fourier transform of the image of a (static) slit object

4.1.1 General case

The stages of image formation in a generalized sampled imaging system are illustrated in Figure 1. The values of the relevant parameters used here are specified in Clause 3.



Key

1 object slit $F_{slt}(r)$

2 lens $D_{lens}(r)$ / $T_{lens}(r)$

3 sampling apertures $D_{ap}(r)$ / $T_{ap}(r)$

4 reconstruction function $D_{rf}(r)$ / $T_{rf}(r)$

Figure 1 — Image formation by a sampled imaging system

For a sampled imaging system we have:

$$F_{img}(r) = \left\{ \sum_k \left[F_{in}(r - k/a) \times \exp\left(i \times 2\pi \times \phi \times (k/a)\right)\right]\right\} \times D_{rf}(r) \quad (1)$$

where

$$F_{in}(r) = F_{slt}(r) \times D_{lens}(r) \times D_{ap}(r); \quad (2)$$

k is an integer (i.e. k = 0,1,2,3...);

ϕ is a phase term describing the position of the slit relative to the sampling array.

NOTE More information on the mathematical relationships involved in imaging with sampled systems can be found in Bibliography references [3] and [4], and in most textbooks dealing with Fourier transform methods.

4.1.2 Special cases

4.1.2.1 General

The relationships listed in this clause are given without derivation (a brief explanation of their derivation can be found in Annex A).

4.1.2.2 Cut-off spatial frequency of $|F_{in}(r)|$ is less than or equal to the Nyquist frequency $1/(2 \cdot a)$

For this condition and for spatial frequencies less than the Nyquist frequency, the system behaves as a non-sampled system and we have:

$$\left|F_{img}(r)\right| = \left|F_{in}(r)\right| \times T_{rf}(r) \quad (3)$$

where

$$\left|F_{in}(r)\right| = \left|F_{slt}(r)\right| \times T_{lens}(r) \times T_{ap}(r) \quad (4)$$

so that

$$T_{sys} = T_{lens} \times T_{ap} \times T_{rf} = \left|F_{img}(r)\right| / \left|F_{slt}(r)\right| \quad (5)$$

4.1.2.3 Cut-off spatial frequency of $|F_{in}(r)|$ is less than or equal to twice the Nyquist frequency (i.e. $1/a$)

For this condition and for spatial frequencies less than twice the Nyquist limit, we get a maximum and minimum value for $|F_{img}(r)|$ as the position of the slit image relative to the sampling apertures of the array is varied. The two values are given by:

$$\left|F_{img}(r)\right|_{max} = \left|\left\{\left|F_{in}(r)\right| + \left|F_{in}(r - 1/a)\right|\right\} \times T_{rf}(r)\right| \tag{6}$$

and

$$\left|F_{img}(r)\right|_{min} = \left|\left\{\left|F_{in}(r)\right| - \left|F_{in}(r - 1/a)\right|\right\} \times T_{rf}(r)\right| \tag{7}$$

from which it can be shown that:

$$T_{sys}(r) = \left|F_{in}(r)\right| \times T_{rf}(r) / \left|F_{slt}(r)\right| = \frac{\left\{\left|F_{img}(r)\right|_{max} + \left|F_{img}(r)\right|_{min}\right\}}{2 \times \left|F_{slt}(r)\right|} \tag{8}$$

for $r < 1/(2\,a)$

and

$$T_{sys}(r) = \frac{\left\{\left|F_{img}(r)\right|_{max} - \left|F_{img}(r)\right|_{min}\right\}}{2 \times \left|F_{slt}(r)\right|} \tag{9}$$

for $r > 1/(2a)$.

It should be noted that in theory the position of the slit, relative to the sampling array, where one obtains $|F_{img}(r)|_{max}$ and that where one obtains $|F_{img}(r)|_{min}$, can be different for each value of the spatial frequency r. This can however only occur if $L_{in}(u)$ is asymmetrical so that there is a significant (non-linear) variation of the associated phase transfer function with spatial frequency. In practise the effect will be small and one can assume that the relevant slit positions are the same for all spatial frequencies.

4.2 Fourier transform of the output from a single sampling aperture for a slit object scanned across the aperture

In this case we define a line spread function $L_{in}(u)$ which is the signal obtained from a single sampling aperture as a function of the position u of a slit in object space (see Figure 2). The modulus of the Fourier transform of $L_{in}(u)$ is given by:

$$\left|F_{in}(r)\right| = \left|F_{slt}(r)\right| \times T_{lens}(r) \times T_{ap}(r) \tag{10}$$

and we have

$$T_{ap}(r) = \frac{\left|F_{in}(r)\right|}{\left(\left|F_{slt}(r)\right| \times T_{lens}(r)\right)} \tag{11}$$