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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

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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.

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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
$F_{img}(r)$
This is given by:

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

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

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

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

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

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

3.1.12
MTF of an imaging pick-up subsystem
$T_{imp}(r)$
product of $T_{ap}(r)$ with $T_{lens}(r)$, where $T_{lens}(r)$ 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
$A_{P,\ imp}$
ratio of the area under $T_{imp}(r)$ 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

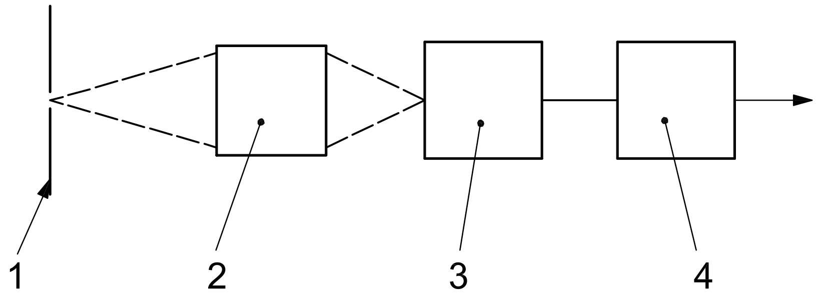
Symbol	Parameter	Units
a	sampling period	mm, mrad, degrees
$1/(2 \cdot a)$	Nyquist spatial frequency limit	mm^{-1}, mrad^{-1}, degree^{-1}
u	local image field coordinate	mm, mrad, degrees
r	spatial frequency	mm^{-1}, mrad^{-1}, degree^{-1}
$L_{\text{ap}}(u)$	line spread function of a sampling aperture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

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

Note that T_{rf} does not appear in these equations and that by re-arranging Equation (11) we have

$$T_{ap}(r) \times T_{lens}(r) = T_{imp}(r) = \frac{|F_{in}(r)|}{|F_{slt}(r)|} \tag{12}$$

where $T_{imp}(r)$ is the imaging pick-up subsystem (provided any anti-aliasing filters be included in the optical train) and is the basis of a measurement of aliasing potential.

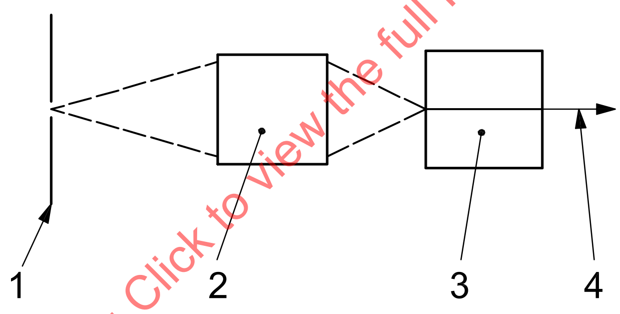
4.3 Fourier transform of the average LSF for different positions of the object slit

If the LSF of the sampled imaging system is measured for many different positions of the object slit relative to the sampling array and the average value of these $L_{av}(u)$ is taken after adjustment to a common slit position, then the Fourier transform of this average LSF is given by:

$$|F_{av}(r)| = |F_{in}(r)| \times T_{rf}(r) \tag{13}$$

and

$$T_{sys} = T_{lens} \times T_{ap} \times T_{rf} = \frac{|F_{av}(r)|}{|F_{slt}(r)|} \tag{14}$$



Key

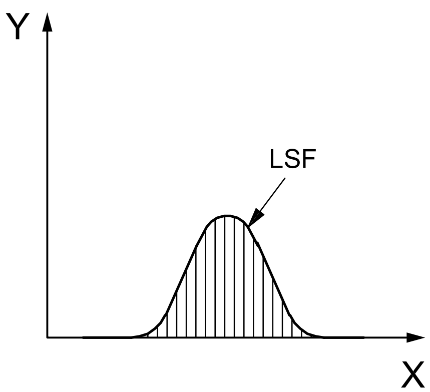
1 slit object $F_{slt}(r)$

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

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

4 output from single sampling aperture [see Figure 2 b)]

a) Schematic measurement arrangement



Key

X position of object slit

Y output from single sampling aperture

b) Illustration of output

Figure 2 — Output from a single sampling aperture as slit object is scanned

5 Methods of measuring the MTFs associated with sampled imaging systems

5.1 General

5.1.1 Range of application

The relationships outlined in Clause 4 can be the basis for suitable measurement techniques.

There are however many different types of sampled imaging system and each can require the use of a different experimental arrangement for implementing these techniques. The main purpose of this International Standard is to specify these relationships and indicate in general terms how they can be applied to measuring the relevant parameters. This International Standard does not describe in detail the measurement techniques for each type of sampled imaging system, but does illustrate the application of a particular method with some specific examples. Most of the measurement techniques and equipment for measuring the MTF of appropriate non-sampled imaging systems may be adapted for testing sampled imaging systems by the methods specified in this International Standard.

5.1.2 Additional measurement considerations

This International Standard shall be used in conjunction with the ISO 9334, ISO 9335 and ISO 11421. These define terms used in the present International Standard, and provide guidelines which have not been repeated here, for achieving accurate measurement of MTF.

Many sampled systems include electro-optic devices that may behave in a non-linear fashion under certain operating conditions. It is important to adjust light levels, etc., so that the MTF measurements are made with the system functioning as far as possible in a linear mode.

5.1.3 Specifying the relevant MTF

In general the most useful of the MTFs specified in this International Standard will be that of the system (i.e. T_{sys}) which, as a minimum, will describe the combined effect of the sampling aperture and the reconstruction function, but may also include other components of a system such as lenses and displays. When quoting MTF values for sampled imaging systems, or devices, it is generally assumed that the values refer to T_{sys} unless otherwise specified. When quoting such values care should be taken to avoid any ambiguities over what constitutes the system.

5.1.4 Test conditions

It is necessary to follow the guidelines set out in ISO 9335 and quote all relevant test conditions associated with a particular measurement of MTF. These will include the spectral response of the measurement system, field positions, focusing criterion, etc.

5.2 Test azimuth

5.2.1 Detector arrays and raster scan devices

For the purposes of this International Standard the MTF of a sampled system that includes a detector array, must refer to a test azimuth. Normally this will be either perpendicular to the row of elements along which the signal is read out, or parallel to them, but may also have other orientations. This also applies to systems that include devices (such as mirror scanners, CRT displays, vidicon tubes, etc.) where an image is generated by a linear raster scan, although in most such cases the system will behave as a sampled system only in the direction perpendicular to the scan lines.

It is important to note that the orientation of the test azimuth can in some cases have significant implications for the detailed manner in which some of the measurement techniques described in 5.3 and 5.4 are implemented. This is particularly so when measurements are being made directly on a video output signal from the system under test. There are two points to note in this case. The first is that the LSF corresponding to a slit object perpendicular to the rows along which the array is read out will appear directly as such in the video signal, but for a slit in the orthogonal direction, the LSF shall be constructed from the video signal on sequential video lines. The second point is that the reconstruction function will be different for the two azimuths and in fact in the latter case it will approximate to a delta function (i.e. $T_{rf}(r) = 1$ for all frequencies).

Methods 5.3.3 and 5.3.4 are in general only applicable to test azimuths in the direction of the rows or columns.

5.2.2 Fibre-optic face plates, channel multipliers and similar devices

For this type of device where, in effect, the output from each sampling aperture generates the corresponding image point directly, test method 5.3.3 allows any test azimuth to be used for measuring the MTF, provided the azimuth used is specified unambiguously with the result of a measurement. In practise it is usual to use azimuths that correspond closely to recognised axes of symmetry in the pattern of sampling apertures.

5.3 Measurement of T_{sys} of a sampled imaging device or complete system

5.3.1 Measurement with cut-off frequency of $|F_{in}|$ less than the Nyquist frequency — Applicable to most types of device

Provided $|F_{in}(r)|$ has a cut-off spatial frequency that is less than or equal to the Nyquist frequency, then we see from Equation (5), that $T_{sys}(r)$ can be determined by calculation from the measured Fourier transform of the image of a static slit object. The effect of any components which make up the measurement system, such as a lens, can be excluded from the value of T_{sys} provided we know its MTF (this can usually be determined by a separate measurement).

The technique is applicable to almost all types of system. The method of measurement for a particular type of system will be the same as that used for a non-sampled imaging system (see ISO 9335) with the important proviso that $|F_{in}|$ [see Equation (5)] fall to zero by the Nyquist frequency.

The cut-off spatial frequency for $|F_{in}(r)|$ can in many cases be appropriately adjusted by selecting a suitable width for the object slit. However, this may not always be the case if the MTF of the lens and that of the sampled imaging system do not sufficiently attenuate the response of the slit beyond its first zero. This difficulty can be overcome by using a slit with an intensity distribution across its width, which has no spurious response beyond its first zero. An example of such a function is a Gaussian distribution {i.e. $L_{slt}(u) = \exp[-\pi \times (c \times u)\ 2]$, where c is a constant that determines the width of the function}. Such slits can be made by etching appropriate patterns in an opaque metal film as illustrated in Figure 3. The arrangement that analyses the final image shall however sample a sufficient length of the slit image to average out the effect of the individual patterns.

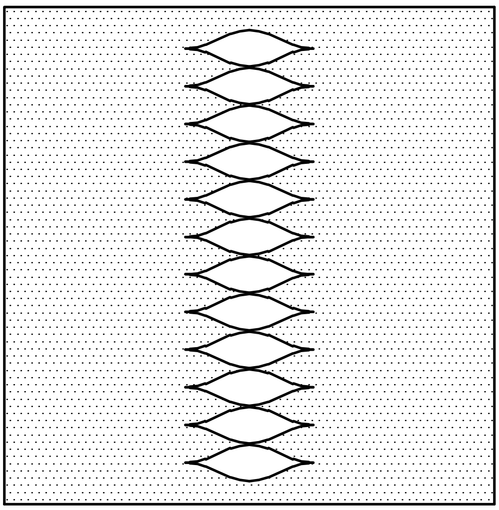


Figure 3 — Example of make-up of a slit with a Gaussian intensity cross section

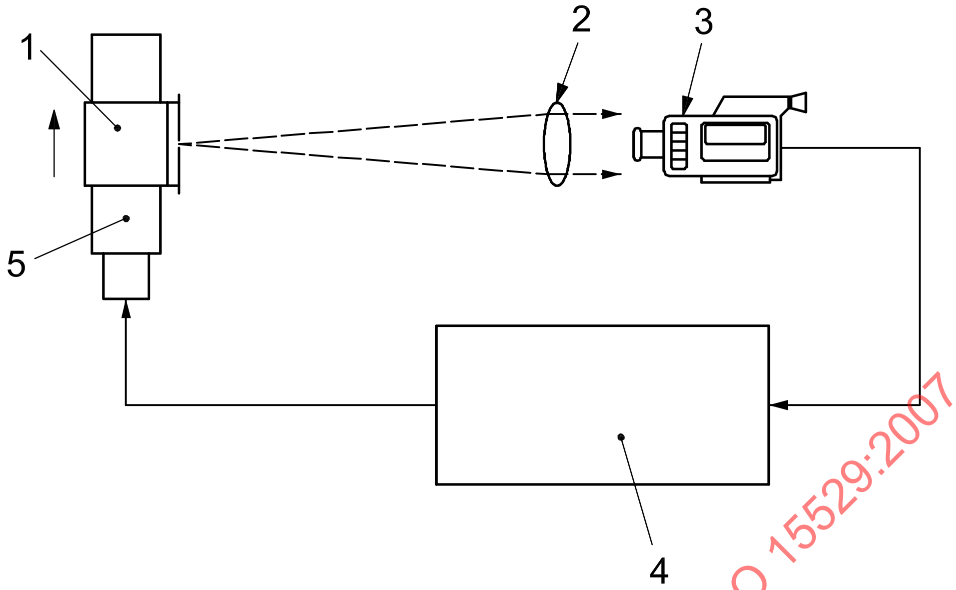
The main drawback to using this measurement technique is that it limits the maximum spatial frequency to which the MTF can be measured to a value less than the Nyquist frequency. In practise the real limit may be as little as half the Nyquist frequency since uncertainties in the exact value of the Fourier transform of the slit (which is applied as a correction factor to the measured MTF) may introduce unacceptably large errors.

An alternative technique which falls in the present category is to actually use a sinusoidal grating as a test target and to determine $T_{sys}(r)$ directly by measuring the ratio of the grating modulation in the final image generated by the system under test to the modulation in the original test target (see ISO 9334 for a definition of MTF in these terms). The MTF can be measured in this way using sinusoidal grating targets of different spatial frequency provided the frequency remains less than the Nyquist frequency.

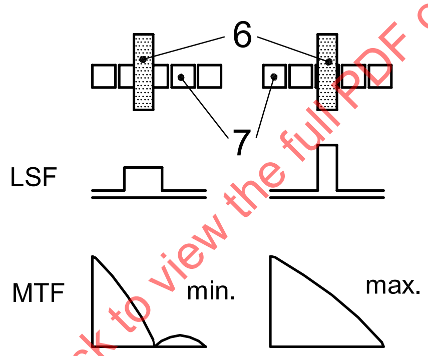
5.3.2 Measurement with the cut-off spatial frequency of $|F_{in}(r)|$ less than or equal to $1/a$, i.e. twice the Nyquist frequency

The relationship of Equations (8) and (9) apply to this measurement technique. To make measurements using this relationship one requires MTF equipment that allows the position of the object slit relative to the sampling array to be varied. Figure 4 diagrammatically illustrates such an arrangement for testing a digital camera using an infinite object conjugate. The illuminated object slit is at the focus of a collimator and is mounted on a motorised micrometer stage which is controlled by the MTF measurement unit. The camera that is being tested is mounted in the collimated beam and its video output signal goes to the MTF measurement unit.

The motorised stage moves the slit object in a direction perpendicular to the length of the object slit and the camera orientation is such that the image of the slit is parallel to the columns, or rows, of the array depending on in which of the two directions the MTF is to be measured.



a) Schematic measurement arrangement



b) Illustration of effect of relative position of slit and array on the LSF an MTF

Key

1 source and slit
2 collimator
3 CCD camera
4 MTF measurement unit
5 motorised micrometer stage
6 slit
7 array

Figure 4 — Equipment for measuring MTF of a digital camera

The measurement procedure consists of moving the slit to a number of different positions and measuring the modulus of the Fourier transform of the slit image at each of these positions. These Fourier transforms are then analysed to determine which corresponds to $|F_{img}(r)|_{max}$ and which corresponds to $|F_{img}(r)|_{min}$ and these are then used in Equations (8) and (9) to determine $T_{sys}(r)$.

The total movement of the slit image shall be greater than one array period (i.e. a) with step sizes no larger than 1/10th of an array period.

Determining which of the measurements is $|F_{img}(r)|_{max}$ and which is $|F_{img}(r)|_{min}$ can be done on the basis of the area under the $|F_{img}(r)|$ curve up to a specified spatial frequency. The latter will normally be equal to about 7/10th of the Nyquist frequency.

It is important to remember that Equations (8) and (9) only hold if $|F_{\text{in}}(r)|$ cuts off at a spatial frequency equal to, or less than, twice the Nyquist frequency.

The use of slit objects with special intensity profiles (see 5.2) can also be an advantage for this technique.

One advantage of this measurement technique, over that described in the previous section, is that in practise it allows T_{sys} to be determined up to and even slightly beyond, the Nyquist frequency. The main justification, however, for using this technique is that the difference between $|F_{\text{img}}(r)|_{\text{max}}$ and $|F_{\text{img}}(r)|_{\text{min}}$ provides a good indication of the level of aliasing to which the imaging system will be subject and it is in fact the basis of the technique for measuring the aliasing function $A_{\text{F, sys}}(r)$ and the aliasing ratio $A_{\text{R, sys}}(r)$ (see Clause 6). If no such differences are found, then the imaging system may be treated as a normal isoplanatic imaging system, which requires no special techniques for measuring its MTF.

5.3.3 Measurement from the average LSF for different positions of the slit object relative to the sampling array using a static object slit

The relationship in this case is given by Equation (13). A particularly simple way of implementing this technique is possible when testing fibre optic imaging devices such as fibre bundles and fibre face plates, or channel plate multipliers.

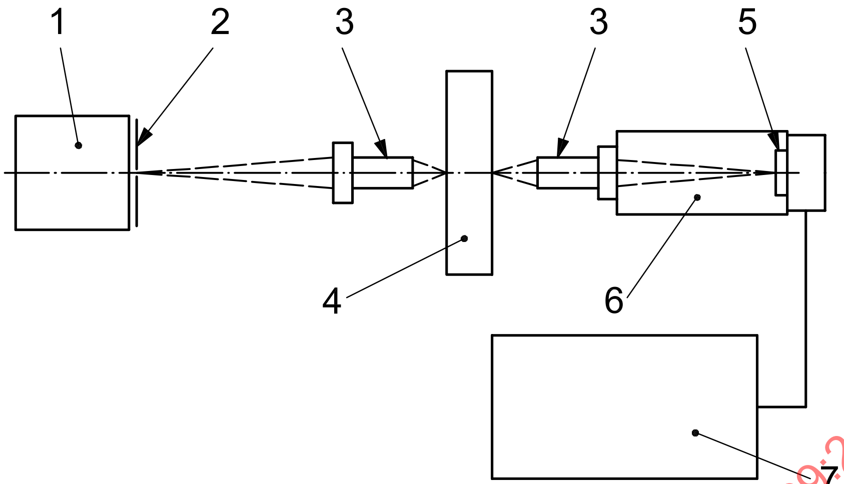
A static slit is used as the test object and the system under test is oriented so that the columns or rows of the sampling array are tilted with respect to the slit, as illustrated in Figure 5. The image of the slit formed by the system under test is then scanned by a micro-photometer system which uses either another slit parallel to the first to obtain an LSF, or as illustrated in Figure 5, uses a linear detector array perpendicular to the image of the slit to measure the LSF. If the orientation of the test system is chosen so that the position of the slit relative to the sampling apertures gradually changes along the length of the slit, then the measured LSF is effectively an average value for different positions of the slit relative to the sampling array.

The Fourier transform of this LSF is the $F_{\text{av}}(r)$ of Equation (13).

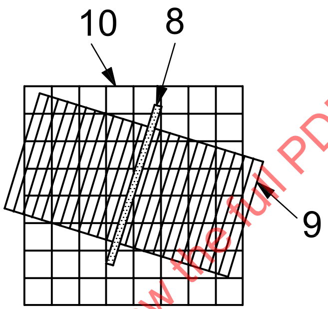
To ensure correct results are obtained, the orientation of the sampling array relative to the slits and the length of the slits, shall be such that the range of relative positions covered is one period, or integer multiples of one period, of the array and that a minimum of ten intermediate positions occurs. Note that this number may be reduced to as little as five provided measurements with the particular device under test indicate that this gives the same result as ten positions.

The technique can also be implemented for devices such as CCD arrays or complete CCD cameras. The procedure in this case (see Figure 6) is once again to tilt the image of the slit projected on to the array so that it is at a small angle with respect to the columns or rows of the array, depending on whether the MTF being measured is that for the direction parallel to the rows, or perpendicular to them. The technique for determining L_{av} will depend on whether measurements are to be made off a display or directly from the video signal generated by the array. In the former case a micro-photometer can be used (in the same way as for a fibre face plate) to scan the LSF generated on the display with its scan direction aligned to be perpendicular to that of the image of the slit. This yields L_{av} directly.

For measurements from the video signal, the procedure is to capture the signal in the frame store of a computer and then to process the signal from each row of the array in order, first of all to determine the position of the centroid of the LSF (i.e. the line which divides the LSF into two equal areas) recorded on each row, then to determine the mean value by which the position of this centroid shifts from one row to the next (using a least squares fit method) and finally to sum the LSFs from all the rows together after having shifted them by the amount previously calculated so that their centroids are all in line. The resulting curve will be L_{av}.



a) Schematic measurement arrangement

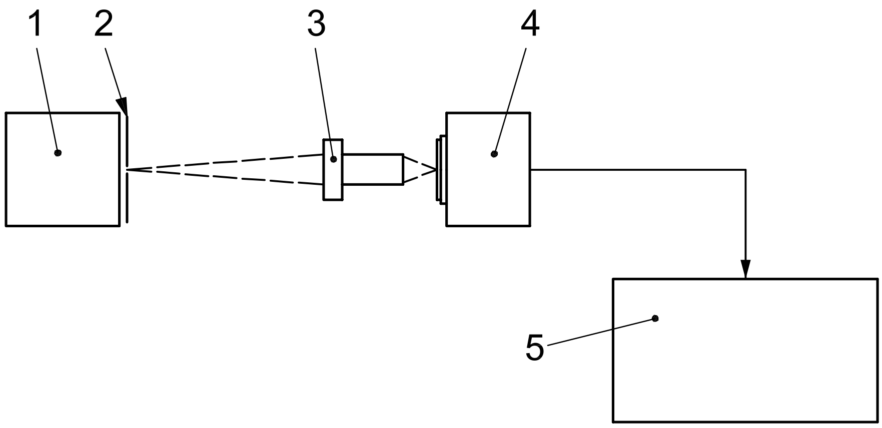


b) Illustration of relative output orientation of main units of the system

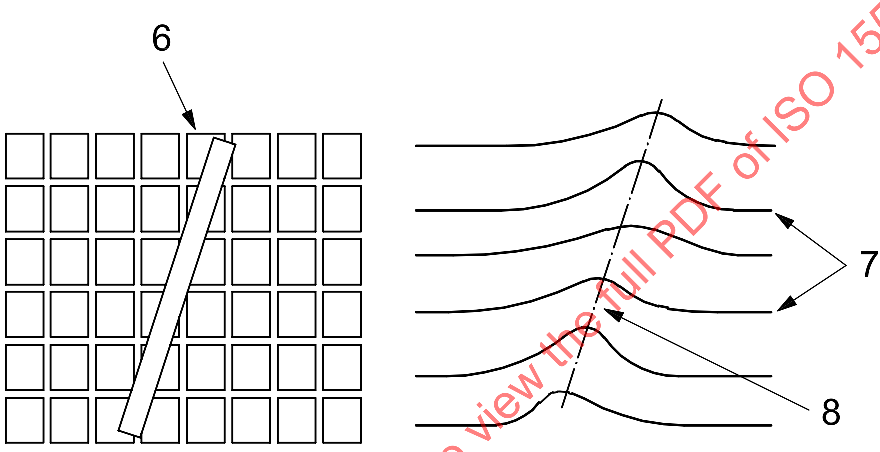
Key

1 source
2 slit
3 relay lenses
4 fibre optics face plate
5 linear detector array
6 micro-photometer head
7 MTF measurement system
8 image of slit
9 forward projection of micro-photometer detector array
10 section of fibre face plate showing relative orientations

Figure 5 — Measurement of MTF of a fibre face plate using a tilted slit



a) **Schematic arrangement**



b) **Illustration of the orientation of the slit with respect to the CCD array and the outputs from each row of the CCD**

Key

1 source
2 slit
3 relay lens
4 CCD array (unit under test) and drive electronics
5 frame store and computer
6 view of the face of the array and image of the slit
7 output from each row of the array
8 least squares fit line through centroid of each LSF

Figure 6 — Arrangement for measuring MTF of a detector array using a tilted slit

5.3.4 Measurement from the average LSF for different positions of the slit object relative to the sampling array using a scanning object slit

In this method (which is applicable to most types of sampled imaging systems) the slit image is aligned to the rows or columns of the sampling apertures (depending for which direction the MTF is being measured). The LSF is measured for a series of known equally spaced positions of the slit image relative to the sampling array. The set of LSF measurements obtained in this way are added together after a positional shift has been applied to each one to remove the known relative shift of the slit image between each measurement. The resulting LSF is equal to L_{av} as specified in 4.3.

The technique can be implemented using the type of arrangement illustrated in Figure 4. In order to obtain meaningful results, the positional shift of the slit image between measurements should not be greater than 1/10th of the array sampling period and the combined shift for all measurements should extend over one or more integer multiples of the period of the array. The positional shift between measurements may be increased up to 2/10th of the array period for specific imaging systems provided measurements indicate that it gives the same results as the spacing of 1/10th.

5.4 Measurement of the MTF of the sampling aperture (T_{ap})

5.4.1 General

The measurement methods described in 5.2 in general all measure the product of T_{ap} and T_{rf} and if one wishes to know T_{ap} on its own one can only do this if one knows T_{rf}. In this clause methods of determining T_{ap} directly are described.

5.4.2 Measurement from the output of a single sampling aperture

For this technique the relationship that applies is given by Equation (11). The equipment requirements are similar to those specified in 5.3 and illustrated in Figure 4, i.e. a means is required of moving the slit relative to the sampling array in a direction perpendicular to its own length and parallel to the rows or columns of the array. The measurement procedure, which is different in this case, requires the MTF measurement unit to build up an LSF by recording the signal from one sampling aperture of the array as the image of the slit object is scanned across it and adjacent sampling apertures. The Fourier transform of the LSF measured in this way, is the $F_{in}(r)$ of Equation (11) and provided we know the MTF of the lens and the Fourier transform of the object slit, we can determine $T_{ap}(r)$ directly.

The distance over which the slit image needs to be scanned must be sufficient to cover the full LSF, i.e. the scan range must extend sufficiently far, either side of the sampling aperture whose output is being measured, that the slit image contributes zero to the output at those positions. The minimum step size will generally need to be less than 1/10th of the array period.

This particular technique allows one to determine $T_{ap}(r)$ directly without having to know $T_{rf}(r)$. In combination therefore with one of the techniques which measures the product $T_{ap}(r) \times T_{rf}(r)$, it is possible to determine $T_{rf}(r)$.

6 Method of measuring the aliasing function, the aliasing ratio and the aliasing potential

The method of determining the aliasing function and the aliasing ratio is to measure $|F_{img}(r)|_{max}$ and $|F_{img}(r)|_{min}$ in the manner described in 5.3.2 using a relatively narrow slit. The aliasing function is then given by:

$$A_{F,\,sys}(r) = \frac{\left(\left|F_{img}(r)\right|_{max} - \left|F_{img}(r)\right|_{min}\right)}{2} \tag{15}$$

And the aliasing ratio by:

$$A_{R,\,sys}(r) = \frac{A_{F,\,sys}(r)}{\left(\left|F_{img}(r)\right|\right)_{av}} = \frac{A_{F,\,sys}(r)}{\frac{\left(\left|F_{img}(r)\right|_{max} + \left|F_{img}(r)\right|_{min}\right)}{2}} \tag{16}$$

In principle this value of the aliasing function and the aliasing ratio is only strictly correct if the width of the test slit is close to zero. In practise measurements are not possible unless the slit has a finite width and therefore for the purposes of this International Standard the slit is regarded as being acceptably small if its width is less than or equal to one quarter of the sampling array period (i.e. slit width $\leqslant a/4$).

The aliasing potential can only be determined directly from a measurement of $T_{\text{imp}}(r)$

$$A_{\text{P, imp}} = \frac{\int_{0,5}^{1,0} T_{\text{imp}}(r) \times \mathrm{d}r}{\int_{0}^{0,5} T_{\text{imp}}(r) \times \mathrm{d}r} \tag{17}$$

The aliasing potential can also be determined by calculating the value of $T_{\text{imp}}(r)$ from separate or combined measurements of $T_{\text{ap}}(r)$, the MTF of the sampling array, and $T_{\text{lens}}(r)$, the MTF of the optical system (including any anti-aliasing filter). We have in this case:

$$T_{\text{imp}}(r) = T_{\text{ap}}(r) \times T_{\text{lens}}(r) \tag{18}$$

$T_{\text{imp}}(r)$ is equal to $T_{\text{sys}}(r)$ in a situation where the effect of the reconstruction function can be eliminated.

The aliasing potential can also be determined by calculating the value of $T_{\text{imp}}(r)$ from separate or combined measurements of $T_{\text{ap}}(r)$, the MTF of the sampling array, and $T_{\text{lens}}(r)$, the MTF of the optical system (including any anti-aliasing filter).

The appropriate equations are given in 4.2 and the associated methods of measurement in 5.4.

When quoting values for $A_{\text{F, sys}}(r)$, $A_{\text{R, sys}}(r)$ and $A_{\text{P, imp}}$, care should be taken to avoid any ambiguities by specifying exactly what constitutes the system. This is important since units of the complete system such as the lens of a digital camera or an associated optical anti-aliasing filter, can play an important part in reducing all these measures of aliasing.

A descriptive note on aliasing, with examples of these various functions, can be found in Annex B.

Annex A
(informative)

Background theory

A.1 Sampled systems and isoplanatism

As indicated in the Introduction, the MTF concept is only fully applicable to an imaging system if it is linear and isoplanatic. A system is isoplanatic if the image of a point object (i.e. the point spread function) is independent of the position of the point in the object plane. When considering imaging in one dimension only, this requirement applies to a line object and the associated line spread function (LSF).

In systems where the image is generated by sampling the intensity distribution in the object at a number of discrete points or lines, the final image of a point or line object varies with very small shifts of the object with respect to the array of sampling points or lines and therefore the imaging system is not strictly isoplanatic. An extreme example of this is illustrated in Figure 4, which shows how a doubling in the width of the LSF can occur by shifting the line object from being centred over a sampling aperture, to being midway between two sampling apertures**.** The associated MTFs obtained by taking the modulus of the Fourier transforms of the two different LSFs are, of course, also very different.

In a practical situation, the LSF of the imaging system, at the image plane where the sampling occurs, has a finite width. The greater the width of this LSF compared to the sampling period, the less significant will be the variation of the final system LSF as the position of the original line object changes and the more precisely the normal MTF concept applies to such systems. This International Standard is intended to specify MTF parameters and methods of test which can be applied to sampled imaging systems that are not isoplanatic and where, therefore, significant changes in the LSF and associated MTF occur as the relative position of object and sampling array alters.

A.2 Explanation of basic equations

A.2.1 General

The equations that are used as a basis for the measurement techniques described in this Internationmal Standard are listed in Clause 4. A brief explanation of how each of these is derived from the basic equation for a sampled imaging system (i.e. $F_{\text{img}}(r) = \{\Sigma_k\ [F_{\text{in}}(r - k/a) \times \exp[i \times 2\pi \times \phi \times (k/a)]]\} \times D_{\text{rf}}(r)$, which is Equation (1), is provided in A.2.2 to A.2.5.

NOTE An explanation of how the basic equation itself is derived is beyond the scope of this International Standard. A full explanation can be found in Bibliography reference [3], as well as in many text books dealing with Fourier theory.

This explanation is made simpler if the basic equation is re-written by putting:

$$F_{\text{in}}(r) = \left|F_{\text{in}}(r) \times \exp\left[i \times \theta_{\text{in}}(r)\right]\right| \text{ so that:}$$

$$F_{\text{img}}(r) = \left\{\Sigma_k \left[\left|F_{\text{in}}(r - k/a)\right|\right] \times \exp\left[i \times \left[\theta_{\text{in}}(r - k/a) + 2\pi \times \phi \times (k/a)\right]\right]\right\} \times D_{\text{rf}}(r) \tag{A.1}$$

A.2.2 Cut-off spatial frequency of $|F_{in}(r)|$ is less than or equal to the Nyquist frequency $1/(2\cdot a)$

See 4.1.2.1.

It is noted quite simply that if the cut-off spatial frequency of $F_{in}(r)$ is $< 1/(2\cdot a)$, then $F_{in}(r - k/a)$ will be zero within the spatial frequency range $0 - 1/(2\cdot a)$ for all values of k except $k = 0$. Within that spatial frequency range therefore:

$$F_{img}(r) = |F_{in}(r)| \times \exp[i \times \theta_{in}(r)] \times D_{rf}(r) \text{ and}$$

$$|F_{img}(r)| = |F_{in}(r)| \times T_{rf}(r) \tag{A.2}$$

A.2.3 Cut-off spatial frequency of $|F_{in}(r)|$ is less than or equal to twice the Nyquist frequency (i.e. $1/a$)

See 4.1.2.2.

In this case $F_{in}(r - k/a)$ may be non-zero within the spatial frequency range 0 to $1/a$ only when $k = 0$ or 1. Within that spatial frequency range therefore we have:

$$F_{img}(r) = \left[|F_{in}(r)| \times \exp\left(i \times (\theta_{in}(r)\right) + |F_{in}(r - 1/a)| \times \exp\left(i \times \left(D_{in}(r - 1/a) + 2\pi \times \phi \times (1/a)\right)\right)\right] \times D_{rf}(r) \tag{A.3}$$

and therefore

$$|F_{img}(r)| = \left[|F_{in}(r)|^2 + |F_{in}(r - 1/a)|^2 + 2 \times |F_{in}(r)| \times |F_{in}(r - 1/a)| \times \right.$$

$$\left. \left[\cos\{\theta_{in}(r) - \theta_{in}(r - 1/a) + 2\pi \times \phi \times (1/a)\}\right]\right]^{1/2} \times T_{rf}(r) \tag{A.4}$$

By varying the position of the slit image with respect to the array, one effectively varies ϕ and there will be a position for which the cosine term in Equation (A.4) is equal to 1. In this case a maximum value for $F_{img}(r)$ results and Equation (A.4) becomes:

$$|F_{img}(r)|_{max} = \left[|F_{in}(r)| + |F_{in}(r - 1/a)| \right] \times T_{rf}(r) \tag{A.5}$$

Similarly there will be a position where the cosine term is equal to –1, in which case a minimum value for $F_{img}(r)$ results and Equation (A.4) becomes:

$$|F_{img}(r)|_{min} = \left[|F_{in}(r)| - |F_{in}(r - 1/a)| \right] \times T_{rf}(r) \quad \text{for } r < 1/(2\cdot a) \tag{A.6}$$

and

$$|F_{img}(r)|_{min} = -\left[|F_{in}(r)| - |F_{in}(r - 1/a)| \right] \times T_{rf}(r) \quad \text{for } r > 1/(2\cdot a) \tag{A.7}$$

By adding together Equations (A.5) and (A.6) and rearranging the terms they become:

$$|F_{in}(r)| = \frac{\left[|F_{img}(r)|_{max} + |F_{img}(r)|_{min} \right] \times T_{rf}(r)}{2} \quad \text{for } r < 1/(2\cdot a) \tag{A.8}$$

By subtracting Equation (A.7) from (A.5) we obtain:

$$\left|F_{\text{in}}(r)\right| = \left[\left|F_{\text{img}}(r)\right|_{\text{max}} - \left|F_{\text{img}}(r)\right|_{\text{min}}\right] \times T_{\text{rf}}(r)/2 \qquad \text{for } r < 1/(2 \cdot a) \qquad \text{(A.9)}$$

As indicated in the main part of this International Standard, the positions of the slit image which give $|F_{\text{img}}(r)|_{\text{max}}$ and $|F_{\text{img}}(r)|_{\text{min}}$ can in principle be different for different values of the spatial frequency r, if $\theta_{\text{in}}(r)$ varies (non-linearly) with r. Even in such circumstances, the errors in assuming that the slit positions are the same for all values of r will in practice be small. One reason for this is that the value of $T_{\text{in}}(r)$ will have fallen to a relatively small level at spatial frequencies where changes in the value of $\theta_{\text{in}}(r)$ become significant.

A.2.4 Fourier transform of the output from a single sampling aperture for a slit object scanned across the aperture

See 4.2.

Equation (10) derives directly from the manner in which $L_{\text{ap}}(u)$ and $T_{\text{ap}}(r)$ are defined in this International Standard (see Clause 3).

A.2.5 Fourier transform of the average LSF for different positions of the object slit

See 4.3.

The average LSF is obtained by measuring the LSF for many different positions of the object slit relative to the sampling array and taking the average value of these after adjustment to a common slit position. The effect of doing this is quite simply to reduce the effective array sampling period a by a factor n, where n is the number of different slit positions used within the distance of one array period (i.e. a/n is the spacing of the positions of the slit). Provided n is sufficiently large that $|F_{\text{in}}(r)|$ has fallen to zero by the time $r = n/(2 \cdot a)$, then the situation described in A.2.2 holds and it is given by:

$$\left|F_{\text{av}}(r)\right| = \left|F_{\text{in}}(r)\right| \times T_{\text{rf}}(r) \qquad \text{(A.10)}$$