Recommendations for

Measurement of the optical transfer function of optical devices

Confirmed
December 2011

Co-operating organizations

The Instrument Industry Standards Committee, under whose supervision these recommendations were prepared, consists of representatives from the following Government departments and scientific and industrial organizations:

British Calibration Service
British Electrical and Allied Manufacturers' Association
British Industrial Measuring and Control Apparatus Manufacturers' Association
British Steel Industry
British Mechanical Engineering Confederation
British Nautical Instrument Trade Association
British Railways Board
Council of British Manufacturers of Petroleum Equipment
Department of the Environment
Electrical Research Association
Electricity Council, the Central Electricity Generating Board and the Area Boards in England and Wales
Electronic Engineering Association
Engineering Equipment Users' Association*
Gauge and Tool Makers' Association
HEVAC Association
Institute of Measurement and Control*
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Institution of Heating and Ventilating Engineers
Institution of Mechanical Engineers
Institution of Production Engineers
Meteorological Office
Ministry of Defence, Air Force Department*
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National Coal Board
National Physical Laboratory*
Oil Companies' Materials Association
Scientific Instrument Manufacturers' Association*
Sira Institute*
Water-tube Boilermakers' Association

The Government departments and scientific and industrial organizations marked with an asterisk in the above list, together with the following, were directly represented on the committee entrusted with the preparation of these recommendations:

British Photographic Manufacturers' Association Ltd.
Department of Trade and Industry
Federation of Manufacturing Opticians
Flat Glass Manufacturers' Association
Illuminating Engineering Society
Institute of Physics and the Physical Society
Ministry of Aviation Supply
Royal Microscopical Society
Individual manufacturers

These Recommendations, having been approved by the Instrument Industry Standards Committee, were published under the authority of the Executive Board on 10 November 1971

The following BSI references relate to the work on these recommendations:
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Contents

Foreword

These recommendations make reference to the following British Standard:

BS 906, *Engineers' parallels (steel).*

These recommendations have been prepared under the authority of the Instrument Industry Standards Committee at the request of both the manufacturers and the users of optical devices and assemblies.

Their principal aim is to establish an objective procedure for use when measuring the performance of optical devices. The measure of performance adopted in these recommendations is the optical transfer function (OTF). Techniques for the accurate measurement of this function have been established in recent years and it now not only forms the basis of reliable test methods but also serves as a means of expressing performance in design specifications.

At this time no other national or international specifications exist which use the OTF as an objective measure of the performance of optical devices.

It is realized that the complete assessment of optical systems may demand further tests, including interferometric examination, veiling glare and distortion measurement, each of which will make possible examination of other aspects of performance, and which may be the subject of subsequent British Standards.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 16, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

These recommendations adopt OTF measurement as an acceptable test method for ascertaining and expressing the performance of optical devices and systems, including image-forming systems or assemblies and lenses but do not normally relate to the separate parts of a multi-component system. In addition, the recommendations are specifically limited to tests on lens or mirror image-forming systems, or combinations of both.

Although a variety of techniques have been used for measuring the OTF, these recommendations only consider methods employing localized apertures, such as slits or edges, or an extended periodic screen such as a grating, as these methods are suitable for precise instrumentation.

Methods of specifying conditions of test and of expressing the results are recommended. Guidance for the operation of OTF measuring equipment is also given, so that accurate results may be achieved.

NOTE The title of the British Standard referred to in these recommendations is given on page ii.

2 Definitions

For the purposes of these recommendations the following definitions apply:

2.1
line spread function

the distribution of intensity across the image of an infinitely narrow self-luminous line object as formed by an optical system or device

2.2
sine-wave grating

a device which has a transmittance that varies sinusoidally in the direction perpendicular to the length of the grating lines

2.3
object modulation

the modulation of the sinusoidal intensity distribution produced by uniform illumination of a sine-wave grating, defined by the equation:

$$\text{modulation} = \frac{\text{intensity maximum} - \text{intensity minimum}}{\text{intensity maximum} + \text{intensity minimum}}$$

an equivalent definition relates modulation to the ratio of the amplitude of variation in the sinusoidal intensity distribution to the mean intensity level. In Figure 1 modulation = β/α

2.4
spatial frequency (*R*)

the reciprocal of the distance between successive maxima of the grating distribution. The unit of spatial frequency is cycles per millimetre (c/mm)

there are certain circumstances, e.g. when testing an afocal system, when the sine-wave grating is imaged at infinity. In such cases a more appropriate unit of spatial frequency is cycles per milliradian (c/mrad)

2.5
image modulation

the image formed by an optical system or device of a sinusoidally varying object intensity distribution is also a sinusoidally varying intensity distribution. Its modulation is defined as for object modulation

2.6
modulation transfer factor

the ratio of image modulation to object modulation at a particular spatial frequency

2.7
modulation transfer function (MTF)

the variation of the modulation transfer factor with spatial frequency. This function is normalized to unity at zero spatial frequency

2.8
phase transfer value (PTV)

the image formed by an optical system of a sine-wave grating may be laterally displaced from a prescribed image position (Figure 1), for instance that predicted by Gaussian optical considerations. This displacement, as measured in units of the image spatial frequency, is the phase transfer value and is quoted in radians, where 2π rad is equivalent to one period of the sinusoidal image distribution

2.9
phase transfer function (PTF)

the variation of the phase transfer value with spatial frequency

from the definition above, this function is zero at zero spatial frequency. It may be made equal to zero at any other spatial frequency, this operation being equivalent to a redefined image position laterally displaced relative to the previous position

2.10
optical transfer function (OTF)

a complex function of which the modulus is the modulation transfer function and the argument is the phase transfer function

an alternative, and mathematically rigorous, definition is that the OTF is the Fourier transform of the line spread function. The modulus of this function is normalized to be unity at zero spatial frequency and the argument is zero at zero spatial frequency

2.11
radial[1] and tangential azimuths *(see Figure 4)*

optical transfer function measurements are defined as applying to the radial azimuth when an extension of a slit or edge object (or of a line in a periodic grating test pattern [see **3.2** 1)] would pass through the optical axis of the system under test

slits, edges or lines of a grating pattern in a direction at right angles to that defined above are referred to as being in the tangential azimuth. In the case where the test pattern consists of a grating masked by a narrow slit, the grating lines are taken for the purpose of these definitions as being always perpendicular to the masking slit

3 General requirements

3.1 Laboratory environment. In order to obtain reliable results it is advisable to contain the measuring equipment within a relatively vibration and dust free environment, with adequate temperature and humidity control. In addition the level and type of ambient light should be such as not to affect the accuracy of OTF measurement. Special consideration should be given to the effects of air turbulence where long optical paths are involved.

3.2 Equipment. The equipment for measuring the OTF of a lens consists of three main items.

1) *An object generator*. This contains a light source, filters [see **4.1.1** 2)] to enable the spectral content of the light to be varied, and the object which is to be imaged by the system under test. The object may consist of a single narrow slit, an edge, an extended grating-like pattern of lines or a similar grating masked by a narrow slit. (The latter system is employed to vary the effective spatial frequency of the grating from zero to a maximum.) The range of spatial frequency may be covered in discrete steps between zero and the maximum spatial frequency, as when using a series of targets of extended grating-like patterns of lines, or may be made to vary continuously. Means should normally be available for rotating the object pattern to enable the OTF of the test system to be measured in radial, tangential and intermediate azimuths. The object generator may include a separate optical channel to act as a reference in the measurement of the phase transfer function.

2) *An image analyser*. This comprises the complementary scanning aperture which is located in the image plane conjugate to the object, a photoelectric detector, signal processing circuits and an output recorder or display.

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[1] Radial and tangential are the preferred terms; the terms "sagittal" and "meridional" have sometimes been used as alternatives.

When the object is a single narrow slit the complementary scanning aperture for direct measurement of the OTF may be either an extended grating or a masked grating with the masking slit perpendicular to the object slit. An alternative scanning aperture for this target and for the edge target is a narrow slit, parallel to the length of the slit and edge, which measures the line and edge spread functions respectively. (Mathematical analysis of these functions is then required to derive the OTF.) When the target is an extended grating the scanning aperture may be a narrow slit parallel to the grating lines and for a masked grating target the scanning aperture may be a narrow slit perpendicular to the masking slit. Means for adjusting the orientation of the scanning aperture about the optical axis of the image analyser should be available to ensure that the conditions of parallelism or perpendicularity mentioned in this paragraph are achieved.

3) *The optical bench*[2]. The purpose of this is to support the optical system under test, the object generator, the image analyser and any ancillary equipment in the manner required for performing prescribed measurements. Where it is necessary to explore the whole image field, not just one diameter of that field, then the optical bench is to have provision for rotating the optical system under test about its optical axis.

The type of configuration used on the optical bench will depend upon the specified test conditions for the optical system under test. Three main possibilities exist:

a) one finite and one infinite conjugate, on-axis and off-axis,

b) two finite conjugates, on-axis and off-axis,

c) two infinite conjugates, on-axis and off-axis.

Any particular optical bench facility will not necessarily permit all three test configurations. In particular, many existing facilities are designed for measurements at one finite and one infinite conjugate, using an auxiliary collimator.

Two typical bench types commonly used are the nodal slide type and the camera type. In both cases it is necessary to maintain the plane of the image analyser slit parallel to the image plane. Figure 2 and Figure 3 show the essential features of each type of bench.

4 Detailed equipment requirements

To ensure that accurate values of OTF are obtained the measurements described in these recommendations should be made under controlled conditions. In particular, wherever instrumental parameters may influence the results they should either be offset by the application of correction factors (see **8**) or, if this is not practicable, they should be taken into account when estimating the accuracy of the measured OTF.

At present, it is not possible to make precise statements concerning accuracies required of component parts of the measuring equipment to give a stated precision of measurement of the OTF for all possible equipments or set-ups. In some of the following subclauses, indications of tolerances are provided which are considered obtainable from good practice.

The purpose of this clause is to indicate those instrumental parameters which require particular attention. Suggested procedures for checking whether some of these requirements are met are given in **8**.

4.1 Object generator characteristics

4.1.1 *Light source*. The following factors should be taken into account.

1) *Stability*. The light source should be monitored for variations in intensity which could significantly affect measurements. Such variations are significant if they occur over periods of time comparable in length to that involved in plotting a single OTF curve.

2) *Spectral characteristic*. The spectral energy distribution of the light source(s) should be known for the spectral range over which the detector is sensitive.

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[2] The term “optical bench” is the general term embracing all types of bench from the very simple to the most sophisticated arrangement.

4.1.2 ***Slits and edges***. The actual slit width obtained for different settings of the slit width control (where this is fitted) should be calibrated, together with the variation in width from point to point along the slit. The co-planarity of the slit jaws should be checked. The optical density of the slit surround or the nominally opaque area of an edge should be of the order of 5 over the spectral range to which the photo-detector is sensitive, and it should be free of pinholes. The straightness of an edge or of the jaws of a slit should also be checked.

4.1.3 ***Modulation and spatial frequency of grating***. With grating-like patterns a record of the variation of Modulation of the fundamental component with spatial frequency and spectral wavelength should be made. This variation is to be reproducible and an appropriate correction is to be applied to measured values of the OTF. The modulation of the pattern should be constant over its full extent.

The actual spatial frequency obtained in the test pattern, for different settings of the spatial frequency control and covering the whole measurement range, should be determined.

In targets where the grating pattern is masked by a slit, the characteristics defined above and in **4.1.2** equally apply.

4.1.4 ***Light emission from object generator***. The polar distribution of the light leaving the object generator should be such that the entrance pupil of an optical system under test is evenly illuminated (any variation of intensity being smooth and symmetrical about the centre of the pupil and preferably less than ± 10 %).

To exclude the effects of coherence, the beam from the object generator should be at least 50 % greater in diameter than the entrance pupil where it intersects the latter.

The uniformity of illumination of the test pattern should also be checked, and any variations present should again be smooth and symmetrical about the centre of the pattern and preferably be less than ± 10 %.

4.2 Auxiliary optical units. The wavefront aberrations of collimators and other test pattern relaying devices such as microscope objectives, over the relevant wavelength range, should be known. The total residual wavefront aberration introduced should be negligibly small and in no circumstances should it exceed one tenth of that likely to be present in the optical system under calibration. In practice it is desirable that the focal length of the collimator should be at least five times that of the lens system under calibration.

4.3 Image analyser characteristics. As indicated in **3.2** 2) the same types of test pattern may be found in either the object generator or the image analyser, and the characteristics described in **4.1.2** and **4.1.3** therefore apply here. There are, in addition, two special features of image analysers which require examination.

1) *Polar sensitivity*. The polar sensitivity of the image analyser system in the vertical and horizontal planes should be measured, and should be consistent with the angular field and relative aperture of the optical system under test.

2) *Spectral sensitivity of photodetector*. The individual spectral sensitivity of each photodetector in use should be known. Such measurements should also be made of combinations of filters and photodetectors used to simulate particular spectral responses. Particular attention should be paid to the effects of oblique incidence on the spectral characteristics of light transmitted by interference filters.

4.4 Characteristics of complete assembly

4.4.1 *Mechanical*

4.4.1.1 *Accuracy of optical benches*. When OTF equipment is used to make measurements over an extended field, it is usually required that the image analyser should move in a plane (the selected image plane) perpendicular to the optical axis of the system under test.

The effect of mechanical errors in the bench is to cause the image analyser to be displaced from this plane by an amount δz (see Figure 5) which depends upon the choice of field position.

Table 1 gives values of δz which correspond to a change of 0.05 in the MTF of an aberration-free lens, for several values of spatial frequency and relative aperture.

These values are based on a choice of image plane such that the rate of change of MTF with δz is a maximum (not the plane in which the MTF has its maximum value at the given spatial frequency).

In the case of a practical lens with aberrations, Table 1 may be used as a guide, but it is advisable to establish for such a lens the required precision by plotting the OTF versus δz curve at one or more suitable fixed spatial frequencies.

Contributory factors making up the total "δz error" of a bench are, for example, wind in the transverse slide-way along which the image analyser moves, error of straightness of this slide-way, misalignment of the slide-way with respect to the face on which the test system is to be mounted, run-out of lens mounting bearings, and errors of flatness of the base on which the moving parts of the bench are supported (the height of the receiving aperture in the image analyser above this base will also need to be considered).

All these factors should be assessed individually in a given bench, but it is also desirable that the overall δz errors should be measured directly. A convenient method for doing this is described in **8.1**.

4.4.1.2 *Accuracy of field angle and test lens orientation settings*. The accuracy with which field angles should be set during a test will always depend on the rate of change of OTF with field angle. It is necessary to ascertain the precision of setting required of each individual test in the light of the accuracy required for the measured OTF.

The precision of the test lens orientation about its optical axis should be approximately ± 1°.

4.4.2 ***Linearity***. The photometric linearity of the complete analysing system should be measured using light modulated at the normal working frequency. Linearity of phase measurement should also be checked. Displacement of the image of the test pattern with respect to the image analyser should result in a linear variation of the phase reading proportional to displacement (see **8.4**).

Table 1 — Bench error δz giving rise to a change of 0.05[a] in MTF for an aberration-free lens (see **4.4**)

δz^b µm (±)						
f-number	*R* c/mm					
	1	5	10	20	50	100
1	54	11	5	2.5	1	0.5
1.4	76	15	8	4	1.5	0.8
2	108	22	11	5	2	1
4	216	44	22	11	4	3
8	432	88	44	22	12	13
16	864	176	88	44	50	410

[a] For a change of 0.10, double these figures. (Intermediate values may be obtained by interpolation, except for those enclosed by thicker lines.)

[b] Wavelength of light (δ) used in the calculation of δz = 0.5 µm.

4.5 Auxiliary electrical apparatus. All electrical equipment used for measurement should possess short term stability to allow the required precision of measurement. Electrical equipment should also possess adequate long term stability to achieve satisfactory repeatability.

Particular attention should be paid to satisfactory earthing.

5 Specification of measurement conditions

In order that the results of an OTF measurement should not be ambiguous, it is necessary to indicate clearly the conditions under which the test was made. It is also necessary in comparing results obtained in different laboratories to adopt a common set of conventions for specifying the various field angles, orientations or separations involved. The full list of test conditions to be specified is given below.

5.1 Object/image conjugates. The distance between object and image should be specified, together with any magnification and the means of identifying which end of the optical system faces the shorter conjugate.

5.2 Spectral characteristics. The spectral characteristics of the complete combination of light source, detector and any colour filters used should be quoted, or, preferably, should be plotted in the form of a graph.

5.3 Datum focal plane. This can be defined by specifying the spatial frequency(3), spectral characteristics, lens aperture, field position (usually on-axis) and azimuth (radial or tangential) at which a particular proportion of the peak MTF value is obtained. For example, one may define the datum focal plane as that (nearer or further from the lens) in which the MTF is one half of the maximum value obtainable on axis at *R* c/mm (tangential) at a stated *f*-number.

5.4 Image plane. If this is not coincident with the datum focal plane, its distance from the latter, referred to the shorter conjugate, should be given in millimetres.

An increase in distance from the lens (at the shorter conjugate) is counted as positive.

5.5 Field angle. The recommended convention is that a point to the right of the axis of the test system, when facing the system from the shorter conjugate position, is located at a positive field angle (see Figure 4).

5.6 Lens orientation. A suitable mark on the lens barrel (such as the fiducial mark for the iris setting ring) should be chosen as a reference mark.

To define the orientation angle, consider a vector having its origin on the test lens axis and pointing in the direction of positive field angles (see Figure 4).

The orientation angle is positive if, when facing the lens from the object/image plane at the shorter conjugate, an anti-clockwise rotation is required to make the vector point to the reference mark.

5.7 Lens aperture. This should be stated.

5.8 Azimuth. This may be radial, tangential or 45°, etc. If any other azimuth is involved then the azimuthal angle should be measured from the radial direction, i.e. radial test pattern lines would be at azimuth 0°.

5.9 Test lens alignment. The reference face used to align the test lens on the optical bench should be clearly specified.

5.10 Direction of light travel. This should be stated.

6 Points requiring special attention during OTF measurements

In **4** are given general requirements which OTF measuring equipment should meet if accurate results are to be obtained, and these apply to every test that is made. Certain other features will, however, vary from one test to another and depend on the particular measurement conditions and test lens characteristics involved. The most important of these points are as follows.

6.1 Slit width correction. Allowance should always be made for the finite width of each slit involved in the measurement of the OTF by multiplying the measured MTF by the appropriate correction factor.

When a slit is used as test object the effective object contrast $T(R)$, as a function of spatial frequency R, for a slit of width a is given by the equation

$$T(R) = \frac{\sin(\pi R\, a)}{\pi R\, a}$$

The correction factor is therefore given by $C(R) = \dfrac{1}{T(R)} = \dfrac{\pi R\, a}{\sin(\pi R\, a)}$

The same expression is valid if the image of a sine-wave grating target, or slit and edge targets, is scanned by a slit of width a, since this scanning slit transmits higher spatial frequencies with reduced amplitude.

If the OTF measuring equipment has both a target slit, of width a, and a parallel image scanning slit, of width b, the correction factor is

$$C(R) = \left(\frac{\pi R\, a}{\sin \pi R\, a}\right) \quad \left(\frac{\pi R\, b}{\sin \pi R\, b}\right)$$

The widths of slits used in the above expressions are always equivalent widths in the image plane or the plane in which spatial frequency is measured.

Figure 7 shows the correction factors for a slit width of 1 μm. For a slit width of N μm the spatial frequency scale should be divided by the factor N.

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[3] Spatial frequencies are referred to the shorter conjugate.

In some OTF measuring equipments the test object consists of a grating masked by a slit which is perpendicular to the scanning slit. Variation of spatial frequency is obtained by rotation of the grating relative to the masking slit, and if ϕ is the angle between the grating lines and the length of the masking slit and if the widths of the masking slit and scanning slit are a and b respectively the correction factor is given in this case by the equation:

$$C(R) = \left[\frac{(\pi R_m\, a \cos \phi)}{\sin (\pi R_m\, a \cos \phi)}\right] \left[\frac{(\pi R_m\, b \sin \phi)}{\sin (\pi R_m\, b \sin \phi)}\right] \times C(o)$$

where $C(o)$ is the correction factor at zero spatial frequency ($\phi = o$), chosen to make the MTF equal to unity.

In this equation R_m is the maximum spatial frequency obtainable, being equal to the reciprocal of the grating period p.

Figure 8 indicates the values of the correction factor obtained when the slit widths a and b are made equal (the commonly adopted procedure) but of different proportions of the grating period. Under such conditions the above equation reduces to the form

$$C(R) = \left[\frac{\pi M \cos \phi}{\sin (\pi M \cos \phi)}\right] \left[\frac{\pi M \sin \phi}{\sin (\pi M \sin \phi)}\right] \times C(o)$$

where $M = \frac{a}{p} = \frac{b}{p}$

The figure indicates that if $M = 0.25$, or less, no correction is necessary, but if the slit widths are increased then correction factors should be applied.

In other OTF measuring equipments the variation of spatial frequency is obtained by rotating the masking slit relative to the grating, the grating lines being kept perpendicular to an illuminated slit in the object plane of the system under test. In this case, the correction factor is given by

$$C(R) = \left[\frac{\sin (\pi R_o\, a)}{\sin (\pi R_o\, a \sec \phi)}\right] \left[\frac{\pi R_o\, b \tan \phi}{\sin (\pi R_o\, b \tan \phi)}\right]$$

where R_o is the spatial frequency of the grating.

6.2 Spatial frequency correction. When carrying out OTF measurements using a collimator to provide an infinite object conjugate, the spatial frequency generated by a test pattern at the focus of the collimator is to be multiplied by the factors:

$\frac{F_c}{F_t} \cdot \cos \theta$ for the radial azimuth

and $\frac{F_c}{F_t} \cdot \cos^2 \theta$ for the tangential azimuth

to derive the spatial frequency of the image produced at the image analyser where F_c and F_t are the equivalent focal length of collimator and test lens respectively, and θ is the field angle involved in the test.

Alternatively, it is strongly recommended that, when the design of the OTF equipment makes this possible, the actual number of cycles per millimetre in the pattern impinging on the image analyser should be measured at one spatial frequency within the range involved in the test. (A method for carrying out this measurement is given in **8.2**.)

The ratio of the measured spatial frequency value to that indicated by the display on the object generator may then be obtained, and every other indicated spatial frequency included in the test at the same field angle should be multiplied by the same ratio. It should be mentioned that the formulae given above do not apply if the system under test suffers from heavy geometric distortion. In such cases, the procedure recommended for direct measurement of the spatial frequency should be followed.

6.3 Width of test pattern. In cases where the MTF curve falls sharply at very low spatial frequencies, an error in the measured result may arise from the use of an insufficient width of test pattern, or, when measuring line or edge spread-functions, from an insufficient length of scan. Means should preferably be available for varying the width of test pattern or scan length in order to check whether such effects are present.

NOTE Where significant amounts of glare and scatter are involved, the angular extent of the object pattern may have significant influence on the modulation of the image.

6.4 Normalization of MTF. Correct normalization of the measured MTF is of vital importance (see also **7.1**). When an OTF equipment is fitted with a normalization control, its setting should be checked at frequent intervals during a series of OTF measurements. In equipments which do not have the facility for generating zero spatial frequency, the frequency R_o at which normalization is carried out (i.e. at which the MTF is made equal to unity) should preferably not exceed one twentieth of that at which the measured OTF of the lens under test reaches an amplitude of 0.5. In addition, the slope of the measured OTF curve at R_o should preferably not exceed δ/R_o, where δ is the assumed overall accuracy of the MTF measurement.

6.5 Adaptor plates. When adaptor plates are used between the lens reference face and the mounting face on the optical bench, the flatness and parallelism of such plates should be known and due allowance made or, alternatively, the δz versus field angle measurements (see **8.1**) should be repeated with the adaptor plate in position on the bench and at the orientation which will be used during the subsequent OTF measurements.

7 Presentation of results

In presenting the results of OTF measurements, complete information about the conditions of test (see **5**) should be given. The following methods of quoting values of MTF and PTF of the OTF are recommended.

7.1 Modulation transfer function (MTF). This should be normalized to the value of unity at zero spatial frequency. Differences in values of the modulus should be quoted as "decimal values" and not as percentages.

When results are given in graphical form, the left-hand ordinate scale should be labelled MTF and numbered from zero to 1.00.

7.2 Phase transfer function (PTF). This should be normalized to zero at a selected, usually the maximum, spatial frequency. Difficulties may arise from the presence of rapid phase reversals associated with "spurious resolution" or as a result of low modulation values. In such cases the phase curve should be normalized to zero at the frequency for which the modulus reaches its first minimum (see point P on the phase curve B in Figure 6) or a value of 0.10, whichever is the lower. When phase values are given graphically the right-hand ordinate scale should be labelled "phase" and marked "0°" at the mid point (opposite 0.50 on the modulus scale) and should run from $+\pi$ rad to $-\pi$ rad.

7.3 Spatial frequency. Unless otherwise specified in graphical presentations spatial frequency is to be shown on a linear scale beginning at zero and which is labelled "c/mm".

It is recommended that spatial frequencies should be referred to the shorter conjugate.

8 Tests on OTF equipment

Methods for testing the performance of various components (**4**) of the OTF measuring system are outlined below.

They are to be regarded only as suggestions: the actual measurement procedures adopted in a given laboratory will of course depend on the ancillary test equipment available, on the design of the OTF equipment itself and on the proposed use.

8.1 Procedure for checking the mechanical accuracy of optical benches. The amount by which the operating point of the image analysing device (for example, the focus of a viewing microscope or the entrance slit of a photoelectric image scanning device) departs from an accurately defined image plane, parallel to the lens mounting face, at different field angle settings of the bench, is measured (see Figure 5).

8.1.1 ***Testing arrangement***. Figure 5 illustrates the recommended method. The reference surface is provided by an engineer's parallel, Grade A to BS 906, which is supported against and aligned with the lens mounting face.

A light-weight, sensitive probe for measuring linear displacement is clamped to the image analysing device in such a manner that the displacements are measured along a line parallel and as close as possible to the "axis" of the analysing system.

8.1.2 ***Procedure***

8.1.2.1 Determine the accuracy of alignment of the reference surface with the mounting face by allowing the probe to contact the face at two widely separated points, noting the difference of the two readings, and comparing this with the difference obtained for corresponding points on the parallel, when this is placed in position against the mounting face.

8.1.2.2 Record the reading of the probe at each setting after the image-analysing unit has been moved to the position it would occupy in an actual lens test at the field angles involved in finite or infinite conjugate measurements.

8.1.2.3 Plot a curve of δz versus field angle θ (see Figure 5), corrected if necessary for the errors of straightness of the reference surface and for the angle it makes with the mounting face.

8.1.2.4 Repeat the operations of **8.1.2.2** and **8.1.2.3** for a number of settings of the distance between image analyser and lens mounting face (covering the range of test lens focal lengths which the bench can accommodate) and a number of settings of the lens mounting face with respect to the axis of rotation of the bench (covering the range of entrance pupil, or — depending on the type of bench — nodal point positions which can be accommodated).

8.1.2.5 Where the bench includes a facility for rotating the test lens about its optical axis, misalignment of the lens mounting face with the axis of rotation, axial displacement occurring during rotation and lack of flatness of the mounting face should be checked by measuring probe displacement as a function of angle of rotation of the lens holder, when the probe is allowed to contact the mounting face at each of two diametrically opposite points.

8.1.3 ***Specified conditions***. A calibration curve, determined to an accuracy of ± 0.5 µm and showing the departure of the reference surface from the best-fitting plane, should be available. This curve should have been obtained with the parallel supported in the manner described in **8.1.1**.

The probe should be calibrated to an accuracy of 1 % or 0.1 µm, whichever is the greater, over the range 0 µm to 100 µm.

8.2 Procedures for checking contrast, mean level and spatial frequency of grating patterns

8.2.1 ***Method***. A narrow slit is positioned in or conjugate to the plane of the test pattern, and the amplitude and mean level of the variations of the light flux it transmits, as it is scanned across the pattern, are measured. If necessary, the pattern may be imaged on the scanning slit using a microscope objective, but the effect of the OTF of the objective is then to be taken into account.

The linearity and accuracy of the spatial frequency display may be checked by plotting the indicated value against the measured displacement of the scanning system corresponding to a single cycle of the test pattern. It is recommended that the measured displacement be made for a number of cycles.

8.2.2 ***Procedure***. Place a suitable photoelectric photometer behind the scanning slit (in some cases the image analysing system will serve) so as to receive the total flux leaving the slit. At each of a number of spatial frequency settings covering the available range, set the slit width to give a maximum amplitude reading (width equal to half the grating period) and record the variation of this reading and of the mean (d.c.) level as the slit moves across the test pattern.

8.2.3 ***Specified conditions***. The photometer should be capable of indicating variations of ± 1 % of the mean of either amplitude or (d.c.) level.

8.3 Procedure for checking polar sensitivity of image analyser. Mount the image analyser on an accurate rotating table, with the centre of its receiving aperture coincident with the axis of rotation. Set up a good quality lens system to image a small source of light (modulated if necessary at the operating frequency of the OTF equipment) in such a way that a cone of rays of relative aperture not exceeding *f*/11 is focused on to the receiving aperture.

Rotate the table, and record the variation of image analyser output with angle of rotation.

8.4 Procedure for checking linearity of amplitude and phase displays. Set up a good quality lens in the OTF equipment to form an on-axis, in-focus image of the test pattern on the image analyser.

Insert a range of accurately calibrated, non-scattering neutral-density filters in front of the light source, and plot a graph of amplitude reading versus filter transmission.

To test the linearity of the phase display, displace the image analyser by micrometer screw (preferably accurate to ± 0.5 µm over the range of measurement) across the image of the test pattern, from one bar to the next, and plot a graph of phase reading versus displacement.

8.5 Procedure for checking the accuracy of the OTF MTF display

8.5.1 ***Method***. A rectangular aperture of accurately known dimensions is placed in the plane of the test pattern (as in **8.2.1**, if a "relay" lens is used its OTF is to be taken into account). The image analyser is arranged to accept the total flux transmitted by the aperture.

Ideally, the amplitude of variation of this flux as the test pattern, of spatial period p, is moved across the aperture should be proportional to:

$$\frac{\sin(\pi\, a/p \cos\theta)}{\pi\, a/p \cos\theta} \times \frac{\sin(\pi\, b/p \sin\theta)}{\pi\, b/p \sin\theta}$$

where a and b are the width and length of the aperture respectively, and θ is the angle the lines of the test pattern make with its longer side.

8.5.2 ***Procedure***. Set the spatial frequency of the test pattern to different values within the range available, and record the output of the image analyser at each setting. Plot a curve of output versus spatial frequency, normalized to unity where the latter is zero, and compare this with the curve calculated from the above expression.

8.5.3 ***Specified conditions***. The length of each side of the rectangle should be known to within ± 1 %.

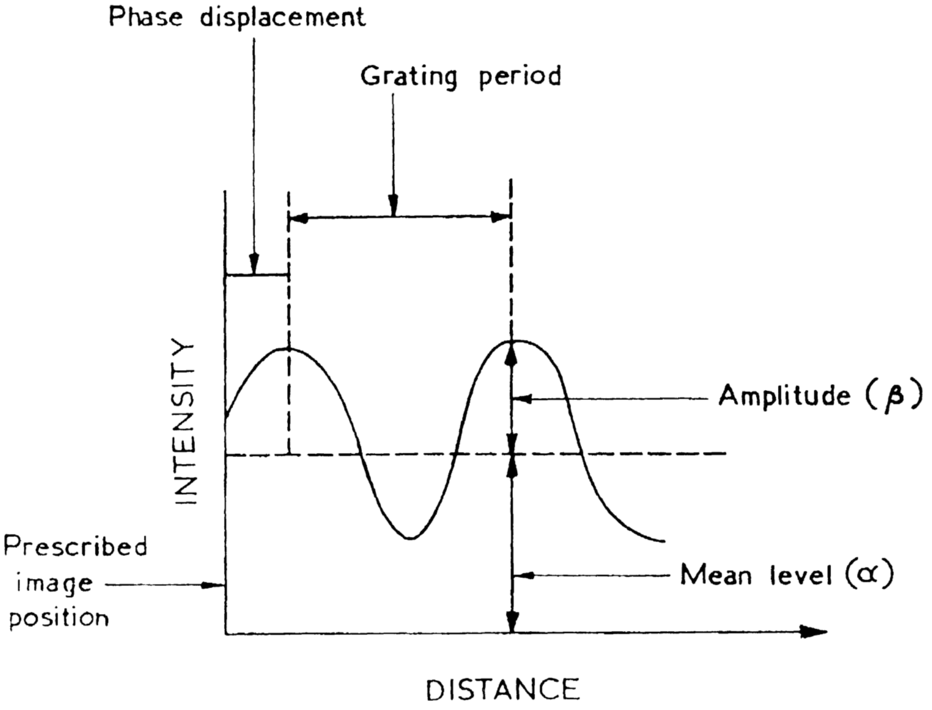


Figure 1 — Definition of phase and modulation (see **2**)

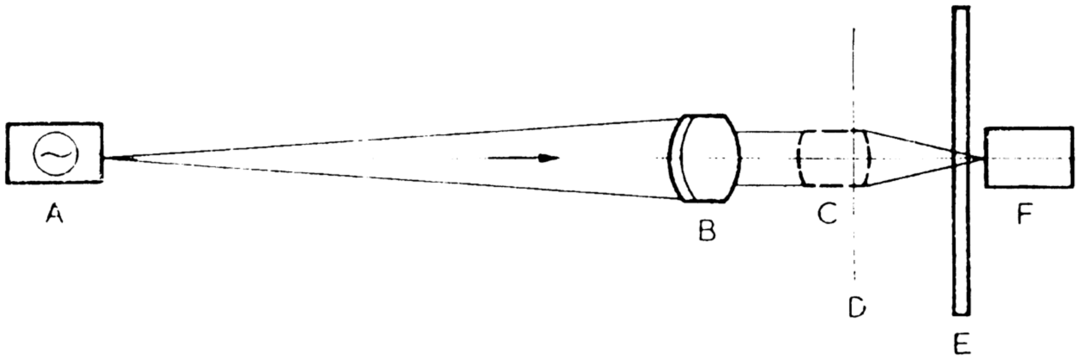


Figure 2a — Axial setting, one finite conjugate and one infinite conjugate

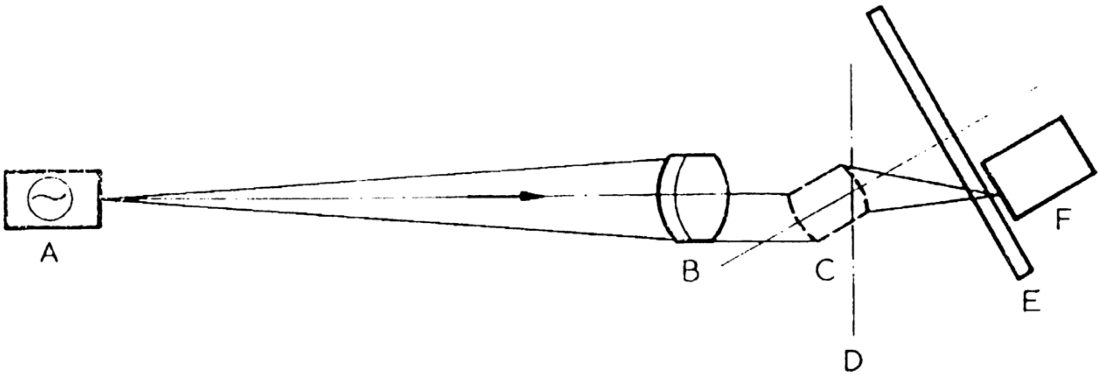


Figure 2b — Off-axis setting, one finite conjugate and one infinite conjugate

A. Object generator[a]
B. Collimator
C. Lens under test
D. Rear nodal point
E. Tee-bar
F. Image analyser

[a] The object generator and image analyser may be interchanged on the bench to meet certain test requirement.

Figure 2 — Nodal slide type bench

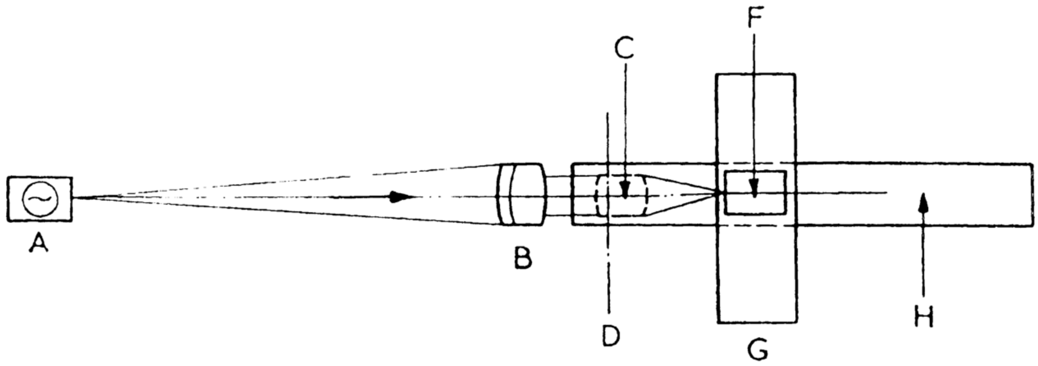


Figure 3a — Axial setting, one finite conjugate and one infinite conjugate

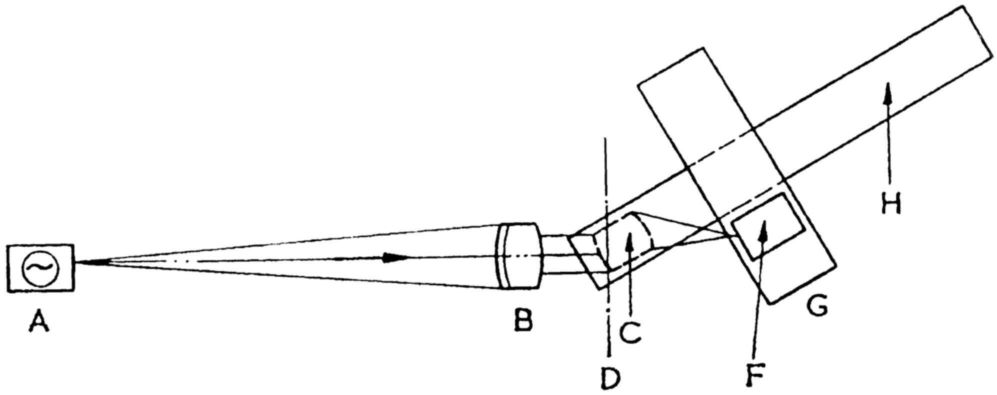


Figure 3b — Off-axis setting, one finite conjugate and one infinite conjugate

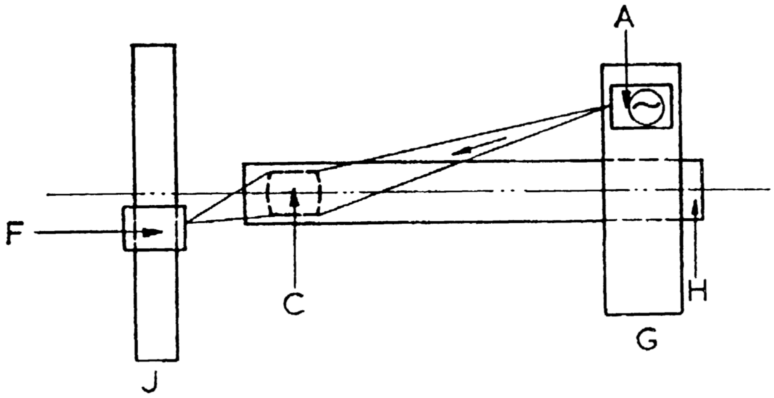


Figure 3c — Off-axis setting, two finite conjugates

A.	Object generator[a]	F.	Image analyser
B.	Collimator	G.	Field slide
C.	Lens under test	H.	Focal slide
D.	Entrance pupil	J.	Field slide

[a] The object generator and image analyser may be interchanged on the bench to meet certain test requirements.

Figure 3 — Camera type bench

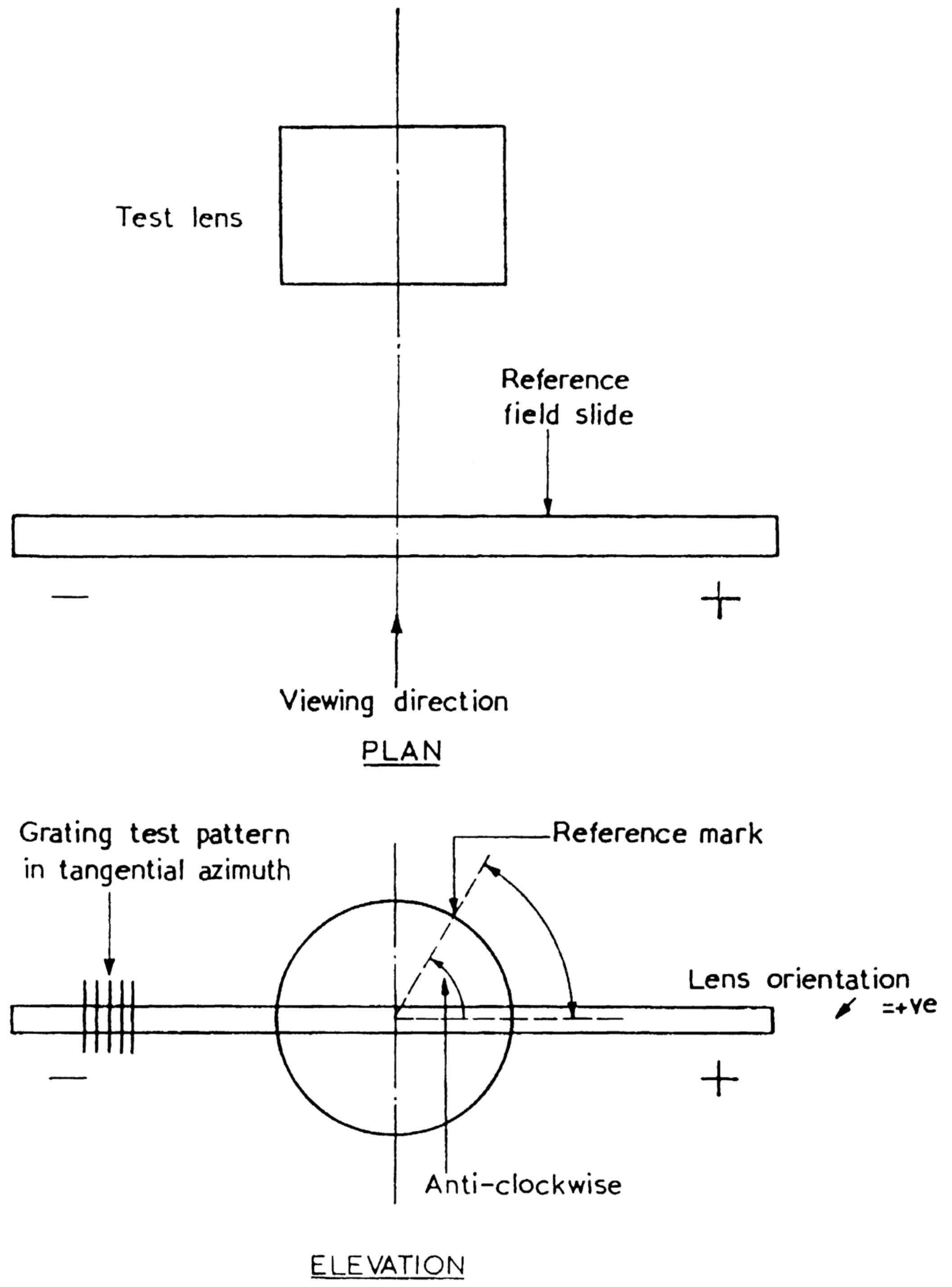


Figure 4 — Sign convention for field direction and lens orientation

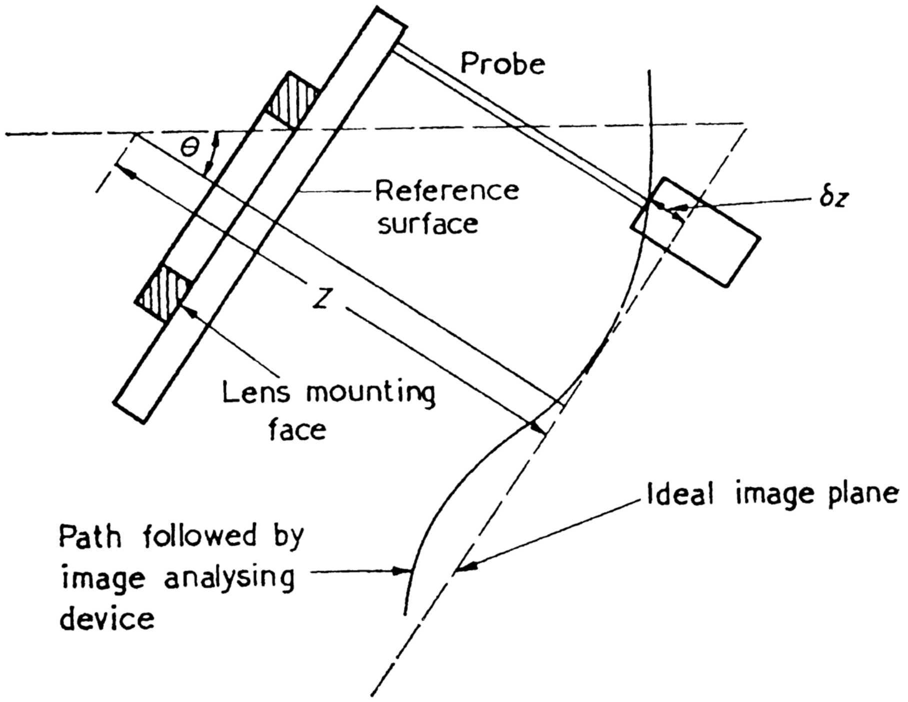


Figure 5 — δz error of an optical bench

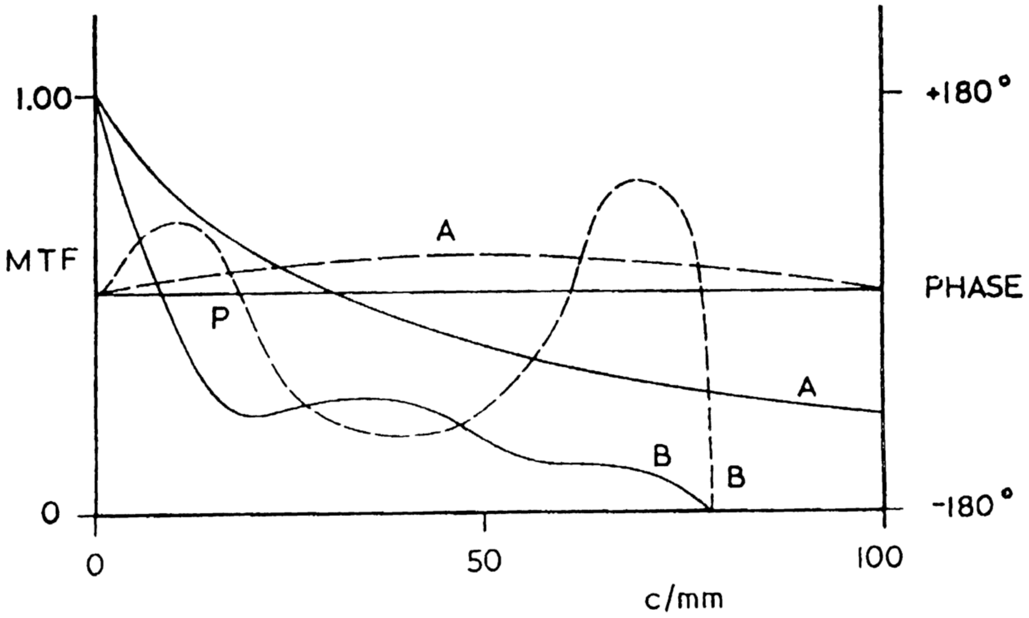
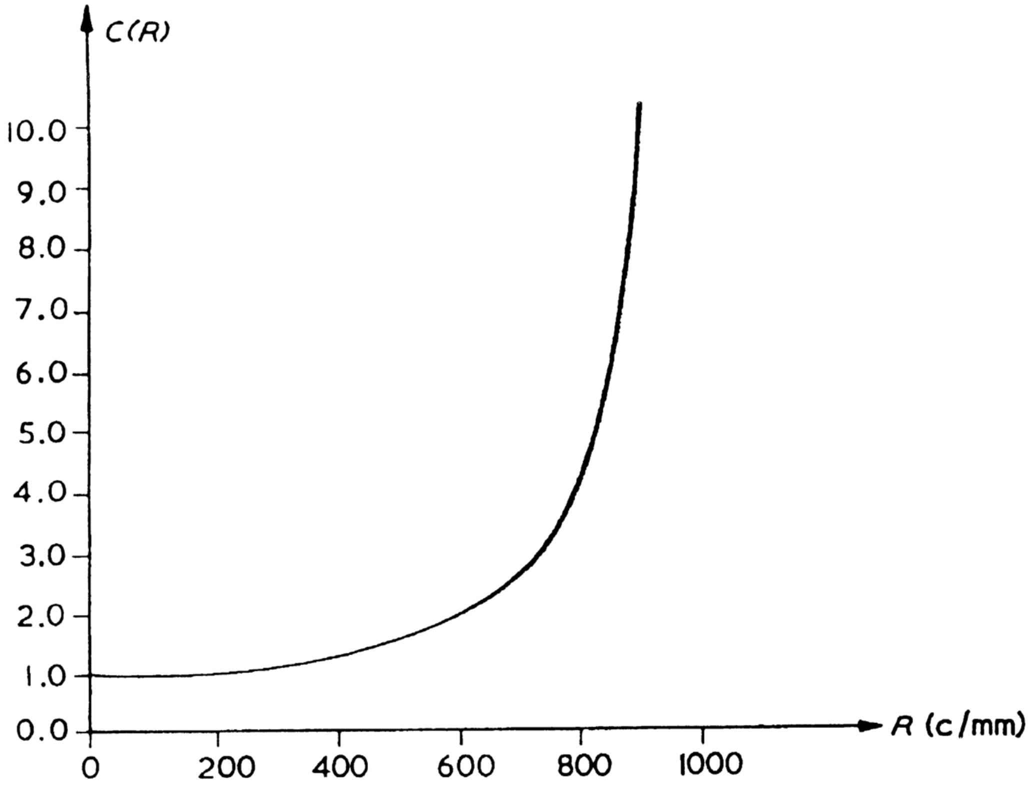


Figure 6 — Presentation of results (see 7)



NOTE For a slit width of *N* μm the spatial frequency scale should be divided by the factor *N*.

Figure 7 — Slit-width correction factors: single slit, width of 1 μm

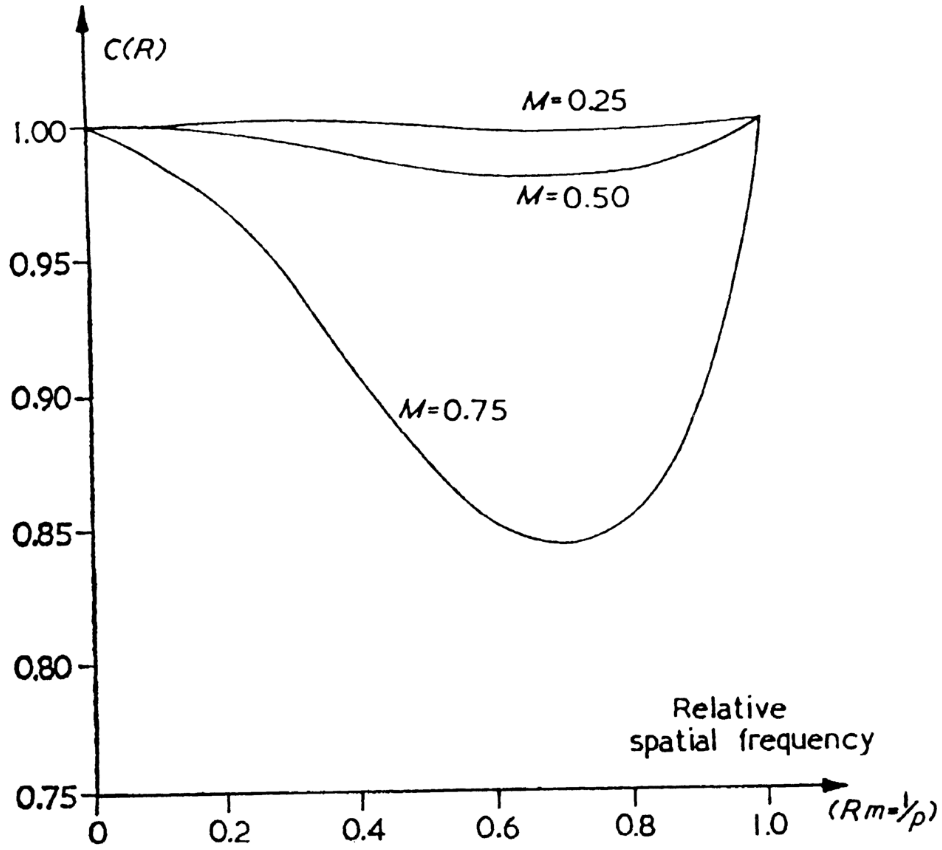


Figure 8 — Slit-width correction factors: crossed slits of equal width (see **6.1**)

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