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Optics and photonics — Spectroscopic measurement methods for integrated scattering by plane parallel optical elements

Optique et photonique — Méthodes de mesure spectroscopique pour la diffusion intégrée par des éléments optiques à plans parallèles

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Foreword

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

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ISO 19962 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental Standards*.

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

Introduction

Light scattering by optical components reduces the efficiency of optical systems and degrades the quality of image formation. Imperfections of the coatings and optical surfaces of the components predominantly produce light scattering. These imperfections involve surface and interface roughness; contamination; scratches; and defects of substrates, thin films and interfaces. Imperfections divert a fraction of the incident radiation from the optical path. The spatial distribution of this scattered radiation is dependent on the power spectral density function of the surface and interface's roughness, on the wavelength of the incident radiation and on the individual optical properties of the component. The wavelength dependence of the scattered radiation is indispensable information for characterizing optical components.

This document proposes a simple spectroscopic method for probing minute scattered radiation using a conventional double-beam spectrophotometer (hereafter, double-beam spectrophotometer) that is widely used for evaluating optical components.

Optics and photonics — Spectroscopic measurement methods for integrated scattering by plane parallel optical elements

1 Scope

This document specifies procedures for determining the spectroscopic forward scattering characteristics of coated and uncoated optical surfaces over a specified wavelength range between 350 nm and 850 nm using a double-beam spectrophotometer with an integrating sphere. This document is also applicable to the forward scattering properties at a single wavelength.

This document is applicable to spectroscopic forward scattering measurements with collection angles larger than 2,7 degrees. ISO 13696 provides a measurement method for smaller collection angles.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

3 Terms, definitions and symbols

3.1 Terms and definitions

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

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1.1
rear surface
surface that interacts last with the transmitted radiation

[SOURCE: ISO 13696:2002, 3.1.3]

3.1.2
forward scattered radiation
fraction of incident radiation scattered by an optical component into the forward half-space excluding that within a cone with a specified angle about the normal direction

Note 1 to entry: The forward half-space is defined by the half-space that contains the beam transmitted by the component that is limited by a plane containing the rear surface of the optical component.

3.1.3
forward scattering
ratio of the power of the forward scattered radiation to the power of the incident radiation

3.1.4
diffuse reflectance standard
diffuse reflector with known total reflectance

Note 1 to entry: Diffuse reflectance standards are usually fabricated from barium sulfate or polytetrafluoroethylene powders. The total reflectance of reflectors freshly prepared from these materials is typically greater than 0,98 within the range from 350 nm to 850 nm, and it can be considered as an 100 % reflectance standard.

[SOURCE: ISO 13696:2002, 3.1.7, modified — deleted NOTE and added Note 1 to entry.]

3.1.5
remaining scattering
ratio of the radiant power detected without a specimen to the radiant power of the incident radiation

3.1.6
minimum scattering collection angle
MCA
minimum angle from which an integrating sphere collects scattered radiation

3.1.7
angle of polarization
angle between the major axis of the instantaneous elliptical polarization state of the incident radiation and the plane of incidence

Note 1 to entry: For non-normal incidence, the plane of incidence is defined by the plane that contains the direction of propagation of the incident radiation and the normal at the point of incidence.

Note 2 to entry: The angle of polarization, γ, is identical to the azimuth, Φ (according to ISO 12005), if the reference axis is located in the plane of incidence.

[SOURCE: ISO 13696:2002, 3.1.9, modified — changed the word of "ellipse" to "elliptical polarization state" and deleted γ as term.]

3.2 Symbols

Symbols used in this document are listed in Table 1.

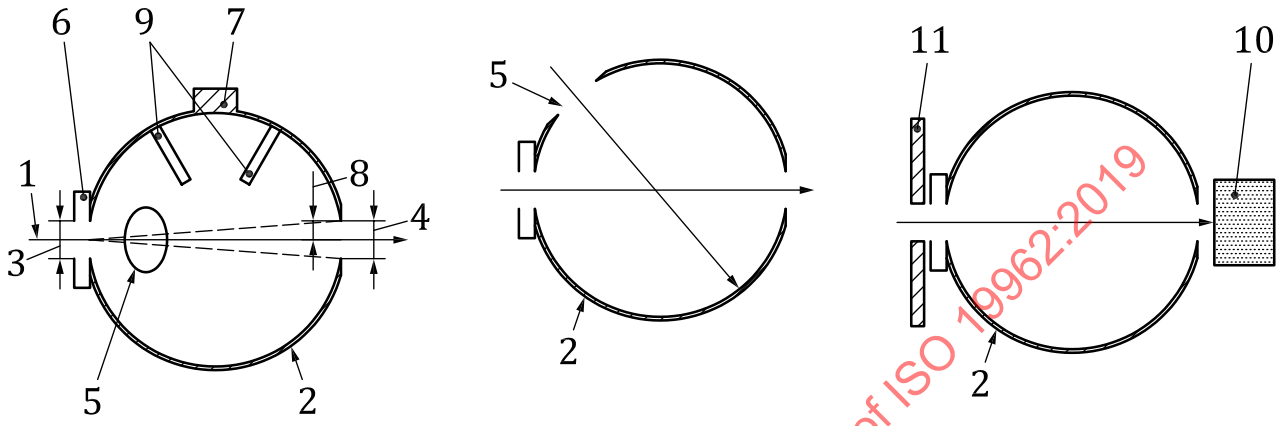
Table 1 — Symbols

Symbol	Term
λ	Wavelength, expressed in nanometres
λ_{start}	Measurement starting wavelength
λ_{end}	Measurement ending wavelength
$S_f(\mathrm{MCA}, \lambda_i)$	Forward scattering at λ_i, MCA
$\overline{S_f(\mathrm{MCA}, \lambda_{start} - \lambda_{end})}$	Mean forward scattering at MCA
$\tau_{st}(\lambda_i)$	Signal value of specimen transmittance as a measurement value of the spectrophotometer
$\tau_{rs}(\lambda_i)$	Signal value of remaining scattering as a measurement value of the spectrophotometer
$\tau_{ss}(\lambda_i)$	Signal value of scattering with specimen (including remaining scattering) as a measurement value of the spectrophotometer

4 Principle

The fundamental principle (see Figure 1) of the measurement apparatus is based on the collection and integration of the forward scattered radiation. For this purpose, an integrating sphere with a diffusely

reflecting coating on the inner surface is used. Beam ports transmit the incident radiation beam into and out of the integrating sphere. The specimen is placed in front of the entrance port. The forward scattered radiation is integrated by the sphere and measured by a detector attached to an additional port. The number, the location, and the shapes of baffles shall be optimized so that any difference in measurement values shall not arise when the same amount of scattered radiation is generated at the entrance and exit ports.



a) Side view **b) Top view** **c) Installation example for reducing remaining scattering**

Key

1	incident radiation	7	detector
2	integrating sphere	8	minimum scattering collection angle, expressed in degrees
3	entrance port		
4	exit port	9	radiation baffles
5	reference port	10	light trap
6	specimen holder	11	shading mask

Figure 1 — Illustration of apparatus to measure forward scattering

5 Measurements using a double-beam spectrophotometer

5.1 General

A double-beam spectrophotometer with an integrating sphere, a very common instrument in almost all organizations related to optical technologies, is used to measure spectroscopic forward scattering characteristics. In this document, a simple and handy way to implement forward scattering measurements is realized. The measurement method described has an easy implementation and is cost-effective.

Since the measured forward scattering strongly depends on the minimum scattering collection angle, the minimum scattering collection angle shall be recorded and considered when comparing the results obtained with different instruments.

The minimum scattering collection angle is determined by the setup of the double-beam spectrophotometer and the geometry of the integrating sphere, in particular the opening angle of the exit port. In this document, the collection angle is larger than 2,7 degrees.

Consult ISO 13696 for angle scattering measurements smaller than 2,7 degrees and realizing lower remaining scattering. ISO 13696 proposes a laser light source based scattering measurement setup

with a minimum scattering collection angle less than 2 degrees and with remaining scattering less than 0,000 15 %.

The minimum scattering collection angle in this document changes from 2,7 degrees to 8,6 degrees depending on the diameter of the integrating sphere, which ranges from 270 mm to 60 mm (see Annex C for additional information). Although the desired remaining scattering value should be one order of magnitude less than the value of forward scattering, it can be challenging with the spectrophotometer setup presented here. In this document the remaining scattering value should preferably be less than 0,02 %. If it is more than 0,02 %, reduction efforts shall be employed such as installing a light trap, shading masks, and shading walls [see Figure 1 c)] as necessary. If a remaining scattering value less than 0,02 % cannot be obtained, it is mandatory that the value shall be recorded and documented. As described in 7.7, the formula for subtracting the remaining scattering contribution shall be used for obtaining the measured forward scattering value.

5.2 Double-beam spectrophotometer

5.2.1 General

The double-beam spectrophotometer used for the spectroscopic forward scattering measurements has four functional sections: the radiation source, the optical system, the integrating sphere, and the detector. These functional sections are described in detail below.

The spectrophotometer shall be able to measure the wavelength range from 350 nm to 850 nm. The wavelength resolution (slit width) shall be 5 nm and stray light shall be 0,000 10 % or less. A user can also specify a wavelength resolution less than 5 nm as long as the dynamic range described in Annex B is preserved.

Using a tungsten-halogen lamp as a light source and a photomultiplier as a detector, the performance certification requirement described in Annex B is satisfied over the wavelength range from 350 nm to 850 nm. This document can also be applied to a wider wavelength range if it is confirmed to meet the performance certification requirement.

5.2.2 Radiation source

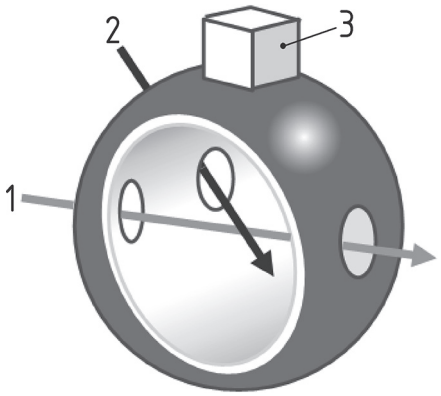
A radiation source with a minimal spectral range of 350 nm to 850 nm shall be used, such as a tungsten halogen lamp.

5.2.3 Optical system

The optical system of the spectrophotometer delivers light emitted by the radiation source to the integrating sphere. The optical system shall have a double-beam configuration with a reference beam and a sample beam. By performing a reference beam intensity measurement and giving its feedback to the sample beam intensity measurement at the same time, the source radiation intensity drift can instantaneously be cancelled.

The optical system shall have a monochromator including a diffraction grating as a dispersive element to obtain monochromatic light with a certain wavelength resolution for irradiating a specimen. For blocking the higher order light diffracted from the grating, an auxiliary prism or an absorption filter may be used. For measurements requiring high spectral resolution and/or low stray light, a double monochromator configuration is recommended.

Although the incident beam to the specimen in the spectrophotometer is polarized in general, polarization does not affect the forward scattering for optically isotropic specimens because the specimen should be irradiated at 0 degree incidence. If the specimen is not optically isotropic, the effect of polarization may be taken into account.



Key

1 incident light
2 reference light
3 detector

Figure 2 — Integrating sphere in the double-beam spectrophotometer

5.2.4 Integrating sphere

An integrating sphere is used for collection and integration of the forward scattered radiation by the specimen. The incident radiation shall be introduced into the integrating sphere at an incident angle of 0 degrees. The integrating sphere shall be equipped with an entrance port and an exit port for the incident radiation beam and another entrance port for the reference beam (see Figure 2). The inner surface shall be coated with a highly diffusive reflecting material with a Lambertian characteristic.

The value of the exit port area divided by the inner surface area of the integrating sphere shall be 0,03 or less and the minimum scattering collection angle [see Figure 1 a)] shall be 2,7 degrees to 8,6 degrees. Radiation baffles may be installed in the integrating sphere to shield the sensitive area of the detector against the direct radiation scattered by the specimen.

"The inner surface area of the integrating sphere" equals the entire surface area of a sphere whose diameter is identical to that of the integrating sphere. The typical inner diameter of the integrating sphere for a conventional spectrophotometer is 60 mm or larger.

5.2.5 Detection system

The detection system shall have sufficient sensitivity, linearity, and dynamic range for the radiation source. Normally, a photomultiplier is attached to the detection port of the integrating sphere with its sensitive area forming a part of the inner surface.

5.3 Test environment

The temperature range and relative humidity of the test environment are defined below.

Temperature: 20 °C to 35 °C

Relative Humidity: 60 % or less

6 Specimen preparation

6.1 Specimen

The specimen shall be a coated or an uncoated plane parallel optical element without any imaging effects and interference between the front and rear surfaces. The imaging effects mentioned here include lens effects and wedge effects changing the beam propagation behaviour inside the integrating sphere. The specimen shall be irradiated by the incident beam at 0 degrees.

6.2 Conditioning of specimen

Storage, cleaning and preparation of the specimen shall be carried out according to instructions given by the manufacturer for normal use.

In the absence of manufacturer-specified instructions, the specimen shall be stored, prepared and tested in an environment with a relative humidity of 60 % or less.

When conditioning is required, condition the specimen in accordance with ISO 291 at (23 ± 2) °C and (50 ± 10) % relative humidity for no less than 40 hours prior to the test.

The specimens shall be kept under cleanroom conditions rated as Class 7 or better at all times during unpacking and preparation. Only non-optical surfaces of the specimen shall be handled.

If contaminants are observed on the specimen or if the original packaging is unsealed under undefined environmental conditions, the surface shall be cleaned using a documented cleaning procedure. If the contaminants are not removable, they shall be documented by photographic and/or electronic means before testing.

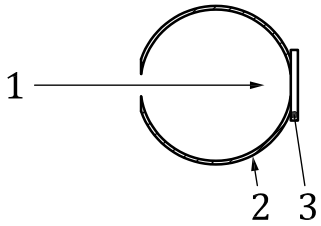
7 Procedure

7.1 Performance certification of double-beam spectrophotometer

The performance of the double-beam spectrophotometer shall be certified according to the description in Annex B.

7.2 Measurement of baseline

Before mounting a specimen, open the entrance port and place a diffuse reflectance standard at the exit port of the integrating sphere, then measure the baseline over the scanned wavelength range (see Figure 3 and Table 2). The shape of the diffuse reflectance standard shall be devised to form a part of the inner wall of the integrating sphere and also shall not degrade any light integrating function. A spectral range for measurement within the range from 350 nm to 850 nm may be specified here.



Key

1 beam
2 integrating sphere
3 diffuse reflectance standard

Figure 3 — Measurement of baseline

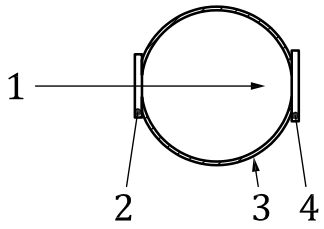
NOTE The reference beam on the integrating sphere for the double-beam measurement configuration is not shown in the drawings.

7.3 Specimen mounting

The specimen is mounted in a holder at the entrance port of the integrating sphere.

7.4 Measurement of specimen transmittance

With the specimen in place, the entrance port is open and the diffuse reflectance standard is placed at the exit port of the integrating sphere. The spectral transmittance, $[\tau_{st}(\lambda_i)]$, is then measured (see Figure 4 and Table 2).



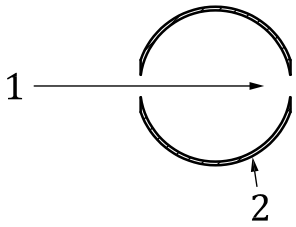
Key

1 beam
2 specimen
3 integrating sphere
4 diffuse reflectance standard

Figure 4 — Measurement of transmittance of the specimen

7.5 Measurement of remaining scattering

After removing the diffuse reflectance standard and the specimen, both the entrance port and the exit port are open. The remaining scattering, $[\tau_{rs}(\lambda_i)]$, is then measured (see Figure 5 and Table 2).



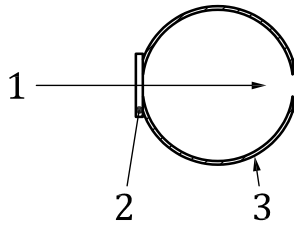
Key

1 beam
2 integrating sphere

Figure 5 — Measurement of remaining scattering inside the integrating sphere

7.6 Measurement of scattering with specimen

The specimen is placed again at the entrance port of the integrating sphere and the exit port is kept open. The scattered light is then measured, $[\tau_{ss}(\lambda_i)]$ (see Figure 6 and Table 2).



Key

1 beam
2 specimen
3 integrating sphere

Figure 6 — Measurement of scattering with the specimen

Table 2 — Status of the specimen and ports for measurements

	Specimen	Exit port
Baseline	No	Diffuse reflectance standard
$\tau_{st}(\lambda_i)$	Yes	Diffuse reflectance standard
$\tau_{rs}(\lambda_i)$	No	Open
$\tau_{ss}(\lambda_i)$	Yes	Open

7.7 Calculation of the forward scattering of the specimen

The forward scattering of the specimen at a wavelength λ_i in the range of 350 nm to 850 nm shall be calculated using the Formula (1). The derivation of the Formula (1) is described in Annex D. The subtraction of the remaining scattering is taken into account with the Formula (1). The data interval should be 1 nm, and a user can also specify the data interval within the range from 0,1 nm to 5,0 nm.

$$S_f(\mathrm{MCA},\lambda_i) = \frac{\tau_{ss}(\lambda_i) - \tau_{st}(\lambda_i)\cdot\tau_{rs}(\lambda_i)}{1-\tau_{rs}(\lambda_i)} \quad (1)$$

where

$\tau_{st}(\lambda_i)$ is the signal value of specimen transmittance;

$\tau_{rs}(\lambda_i)$ is the signal value of remaining scattering;

$\tau_{ss}(\lambda_i)$ is the signal value of scattering with specimen (including remaining scattering).

Please note that the signal to noise ratio of $S_f(\mathrm{MCA}, \lambda_i)$ shall be checked, especially when the $S_f(\mathrm{MCA}, \lambda_i)$ is around 0,001 % or less. It shall be judged whether the measurement is reliable enough for adoption. If the measurement is not reliable enough for adoption, it shall be excluded and shall be documented. The lower reliable limits of $\tau_{st}(\lambda_i)$, $\tau_{rs}(\lambda_i)$ and $\tau_{ss}(\lambda_i)$ used for calculating $S_f(\mathrm{MCA}, \lambda_i)$ become 0,001 % when the OD (optical density) 5 dynamic range of the spectrophotometer is confirmed according to Annex B.

7.8 Calculation of the mean forward scattering of the specimen

Formula (2) shall be used for the calculation of the mean forward scattering over a certain wavelength range. A user can specify a wavelength range of interest. The value of the mean forward scattering shall be calculated over the specified wavelength range.

$$\overline{S_{\mathrm{f}}\left(\mathrm{MCA},\lambda_{\mathrm{start}}-\lambda_{\mathrm{end}}\right)}=\frac{\sum_{i}^{n}S_{\mathrm{f}}\left(\mathrm{MCA},\lambda_{i}\right)}{n} \tag{2}$$

where

$S_{\mathrm{f}}(\mathrm{MCA}, \lambda_i)$ is the forward scattering at the i-th wavelength;

λ_i is the i-th equally spaced wavelength;

n is the number of $S_{\mathrm{f}}(\mathrm{MCA}, \lambda_i)$ over a range.

Please note that the mean forward scattering shall be calculated with the values $S_{\mathrm{f}}(\mathrm{MCA}, \lambda_i)$ that are not excluded in terms of a signal to noise ratio as described in 7.7.

7.9 Uncertainty budget

The main uncertainty factors of double-beam spectrophotometers are described in Clause 9 of ISO 15368:2001. The double-beam spectrophotometers to be used in this document should meet the numbers written in ISO 15368:2001. An example of an uncertainty budget with a double-beam spectrophotometer is given in Table 3.

Table 3 — An example of an uncertainty budget with a double-beam spectrophotometer

Component	Uncertainty
Wavelength accuracy	±0,2 nm
Non-linearity (systematic error)	0,6 %
Photometric fluctuations (random error)	±0,3 %
Stray light	0,000 1 %

8 Test report

The test report shall include the following information:

a) Information on the testing laboratory

   1) name and address of the testing organization;

   2) date of test;

   3) name of the operator of the spectrophotometer;

   4) references to the International Standards used as a basis for the test.

b) Information on the specimen

   1) manufacturer of the specimen, part identification code, date of production;

   2) description of the specimen (materials, coating, polishing, diameter and thickness);

   3) specifications of the manufacturer for storage and cleaning;

4) specifications of the manufacturer for normal use (spectral characteristics, wavelength, polarization, angle of incidence, purpose).

c) Information on the test

1) spectrophotometer (manufacturer, model name and performance certification results);

2) parameters of the integrating sphere (diameter, number of ports, each port size, exit port area, minimum scattering collection angle and wall coating material);

3) parameters of the optical system (wavelength range, radiation source, detector and angle of incidence to the specimen);

4) test environment (temperature, humidity, place information, cleaning before test);

5) state of polarization.

d) Measured results

1) a specified wavelength range for measurement, a specified wavelength resolution (slit width) and a specified data interval;

2) measured $\tau_{st}(\lambda_i)$ data as a function of wavelength;

3) measured $\tau_{rs}(\lambda_i)$ data as a function of wavelength;

4) measured $\tau_{ss}(\lambda_i)$ data as a function of wavelength;

5) calculated $S_f(\mathrm{MCA}, \lambda_i)$ data as a function of wavelength;

6) calculated $\overline{S_f\left(\mathrm{MCA}, \lambda_{start} - \lambda_{end}\right)}$ value and its specified wavelength range;

7) excluded measurement data for $S_f(\mathrm{MCA}, \lambda_i)$ and $\overline{S_f\left(\mathrm{MCA}, \lambda_{start} - \lambda_{end}\right)}$, if any.

The graphical versions showing measured data of 2), 3), 4) and 5) are given in Annex A.

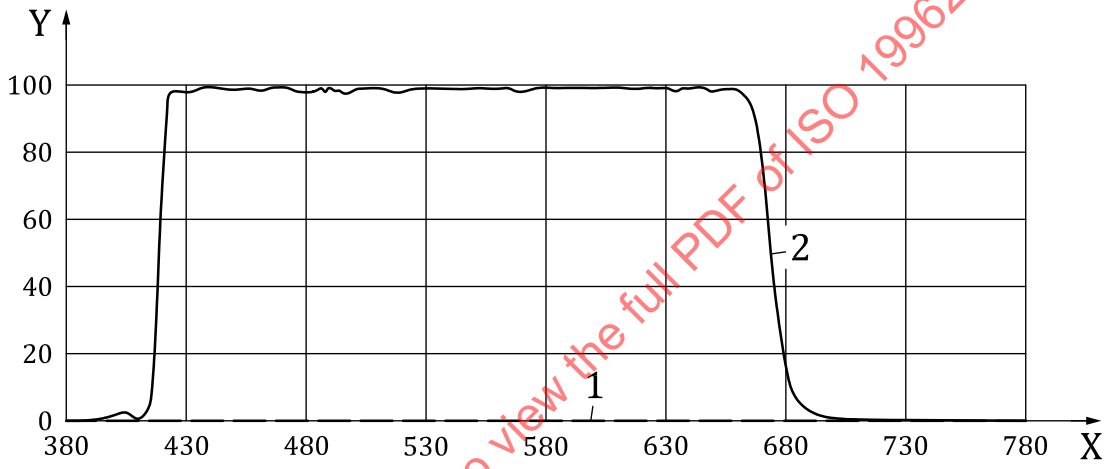
e) Information on the results

1) details of any incidents likely to have affected the results.

Annex A
(informative)

Measurement examples of the specimen transmittance, remaining scattering and scattering with a specimen

The typical specimen transmittance spectrum [$\tau_{st}(\lambda_i)$] and scattering with a specimen [$\tau_{ss}(\lambda_i)$] are overlaid in Figure A.1. A double-beam spectrophotometer is employed with a 60 mm diameter integrating sphere whose MCA is 8,6 degrees. The specified wavelength range for measuring forward scattering of the specimen is from 380 nm to 780 nm.

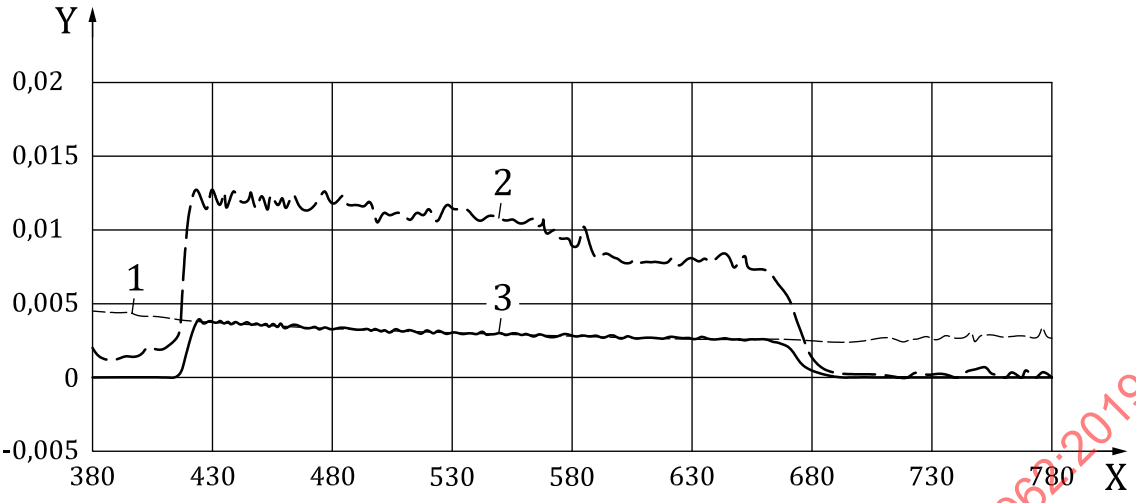


Key

1	$\tau_{ss}(\lambda_i)$	X	wavelength in nm
2	$\tau_{st}(\lambda_i)$	Y	signal [%]

Figure A.1 — The typical spectra of specimen transmittance [$\tau_{st}(\lambda_i)$] and scattering with a specimen [$\tau_{ss}(\lambda_i)$]

The typical scattering spectrum of $\tau_{rs}(\lambda_i)$, $\tau_{ss}(\lambda_i)$ and $\tau_{st}(\lambda_i) \cdot \tau_{rs}(\lambda_i)$ are overlaid as shown in Figure A.2.



Key

1 $\tau_{rs}(\lambda_i)$

2 $\tau_{ss}(\lambda_i)$

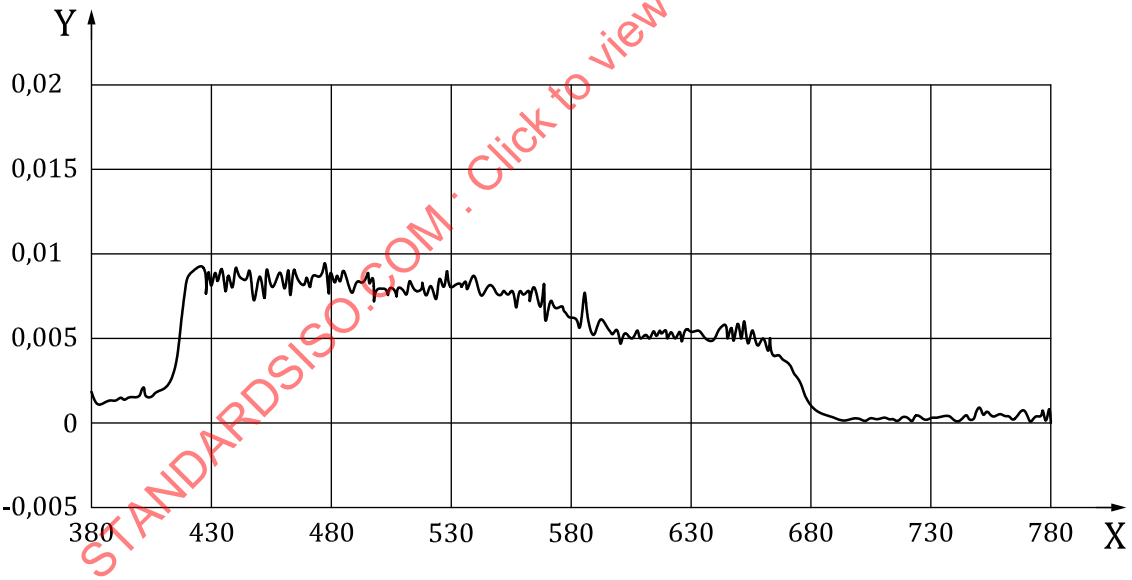
3 $\tau_{st}(\lambda_i) \cdot \tau_{rs}(\lambda_i)$

X wavelength in nm

Y signal [%]

Figure A.2 — The typical spectrum of $\tau_{rs}(\lambda_i)$, $\tau_{ss}(\lambda_i)$ and $\tau_{st}(\lambda_i) \cdot \tau_{rs}(\lambda_i)$

The forward scattering $S_f(8{,}6°, \lambda_i)$ calculated from data in Figure A.2 with Formula (1) is shown in Figure A.3.



Key

X wavelength in nm

Y $S_f(8{,}6°, \lambda_i)$ [%]

Figure A.3 — The forward scattering of a thin film filter specimen

Annex B
(normative)

Performance certification of a double-beam spectrophotometer

B.1 General

For spectroscopic forward scattering measurements, the instrument performance certification procedures for the photometric linearity (B.2) and photometric dynamic range (B.3) should be carried out prior to practical application. In addition, the instrument error should be checked using commercially available certified standard materials.

B.2 Photometric linearity test

Solutions with several degrees of turbidity are prepared as standards for this evaluation. By measuring the scattering of the standards, a calibration plot of scattering as a function of the degrees of turbidity is made and linearity is evaluated with the correlation coefficient of the plot. The procedure is described below.

a) A commercially available turbidity standard solution is diluted with a proper amount of pure water to make a series of turbidity standard solutions as standards for this evaluation. At least five standards in a range of turbidity from 0,1 to 5,0 shall be prepared.

b) A quartz cell with a 10 mm optical path shall be prepared and filled with pure water. As described in Clause 7, the cell is mounted in the specimen holder and $\tau_{rs}(\lambda_i)$ with additional scattering generated by the cell shall be measured. Then, the quartz cell is filled with each turbidity standard and the scattering is measured. For each measurement, care shall be taken to maintain precision: a quartz cell with minimal scratches and contamination shall be selected, and good position repeatability when mounting of the quartz cell (at the entrance port of the integrating sphere) shall be ensured.

c) The scattering of the turbidity standards shall be obtained using Formula (1) described in 7.7. The plot of the scattering measurement results as a function of their degrees of turbidity shall be made and the linearity of the plot shall be evaluated and checked to see if the correlation coefficient is greater than 0,995 and if the line of the plot passes near the origin.

B.3 Photometric dynamic range test

The double-beam spectrophotometer with an integrating sphere shall be certified to have a photometric dynamic range over OD 5. For this test, a set of certified neutral density filters such as OD 1, OD 2 and OD 4 can be used both individually and in combination. By comparing the measured absorbance spectrum and mathematical calculation result of these filter sets, it can be certified that the instrument has a photometric dynamic range over OD 5 within a necessary wavelength region. This test shall be performed with the measurement setup described in 7.4 and Figure 4. Double-beam spectrophotometers proven to be capable of measuring scattering after completion of the evaluations described in B.2 and B.3 may still have a small difference in measured scattering values. In that case, additional tuning may be carried out with haze standards of ASTM D1003 conformity.

Annex C
(informative)

Influence of minimum scattering collection angle to measured forward scattering

A measured forward scattering value is different with a minimum scattering collection angle. It is important to know what minimum scattering collection angle is used and to recognize this influence. The minimum scattering collection angle is mainly determined by an exit port diameter of the integrating sphere that is designed to work well with a double-beam spectrophotometer. Table C.1 shows examples of the integrating spheres and their minimum scattering collection angles.

Since it is well known that each surface has its own ARS (Angle Resolved Scattering), it is meaningful to estimate the influence of the minimum scattering collection angle with typical ARS data. Figure C.1 shows typical ARS data of a surface having isotropic surface roughness, which is usually justified for ground, polished, and coated surfaces. Once a minimum scattering collection angle is specified, a forward scattering value can be calculated by integrating the ARS data in Figure C.1. By repeating this calculation while changing the minimum scattering collection angle, information on the influence of the minimum scattering collection angle on the forward scattering value can be obtained. Figure C.2 shows a plot of collection ratio as a function of the minimum scattering collection angle. The collection ratio introduced here is defined as a ratio of the forward scattering value with a minimum scattering collection angle to the forward scattering value whose minimum scattering collection angle is 2 degrees.

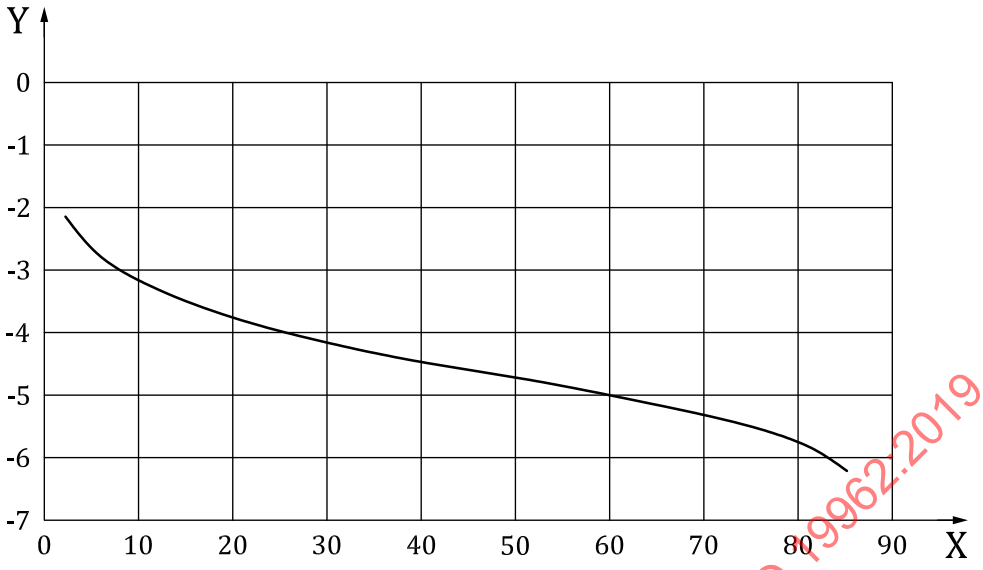
It should also be clearly stated here that the curve shape of ARS varies with the type of coating and surface polish. Although this is not an example of forward scattering but that of backward scattering, Figure C.3 shows the ARS of highly reflective dielectric multilayer coating at 1 064 nm. Figure C.4 is the backward scattering calculated by integrating the ARS of Figure C.3 with different minimum scattering collection angles of integration. Figure C.4 shows that the influence of the minimum scattering collection angle on the backward scattering value is relatively small with the coating in Figure C.3 because the ARS data of the coating drops by only about two orders of magnitude from 2 degrees to 50 degrees. At the other end, there is a metallic mirror coating. Its ARS may drop by several orders of magnitude within a few degrees at small angles, so it is important that the minimum scattering collection angle should be as small as possible in this case. ISO 13696 shows an example of a scattering measurement system with a minimum scattering collection angle less than 2 degrees.

Furthermore, a larger beam diameter on the specimen surface may have an influence on the minimum scattering collection angle. A certain scattering generating point in the footprint of the incident light on the specimen surface has its own minimum scattering collection angle because the exit port position is fixed. If necessary, this effect may also be taken into account.

It is always desired that the measured forward scattering values are obtained with the identical spectrophotometer. If different spectrophotometers are used, the minimum scattering collection angle should be checked to ensure it is identical within a certain angle range. The certain angle range may be less than ±0,4 degrees. The ±0,4 degrees range corresponds to the difference of measured forward scattering values less than 10 % in the case of Figure C.2.

Table C.1 — An example of parameters with the integrating spheres

Integrating sphere diameter	Exit opening diameter	Minimum scattering collection angle
60 mm	19 mm	8,6°
150 mm	25 mm	4,4°
270 mm	25 mm	2,7°

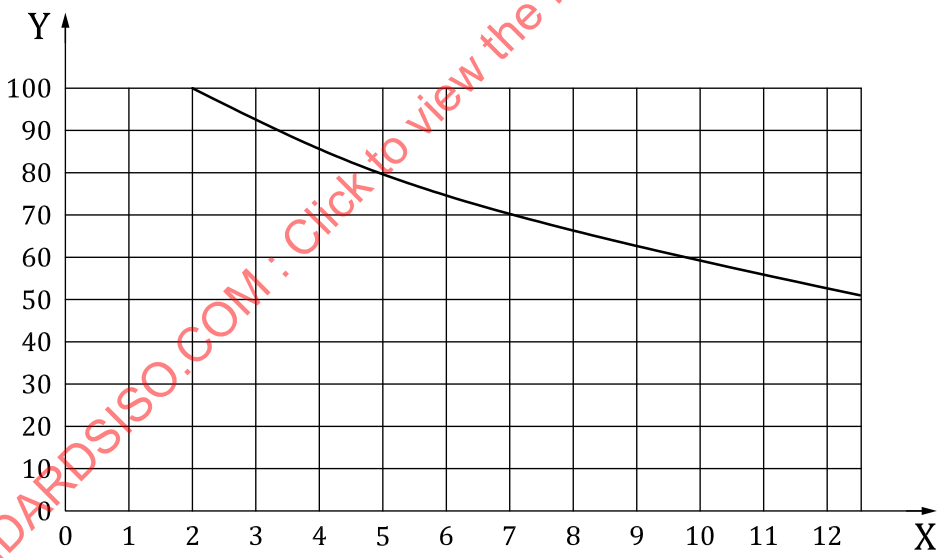


Key

X scattering angle [degree]

Y ARS [1/sr]

Figure C.1 — Typical ARS data of a surface

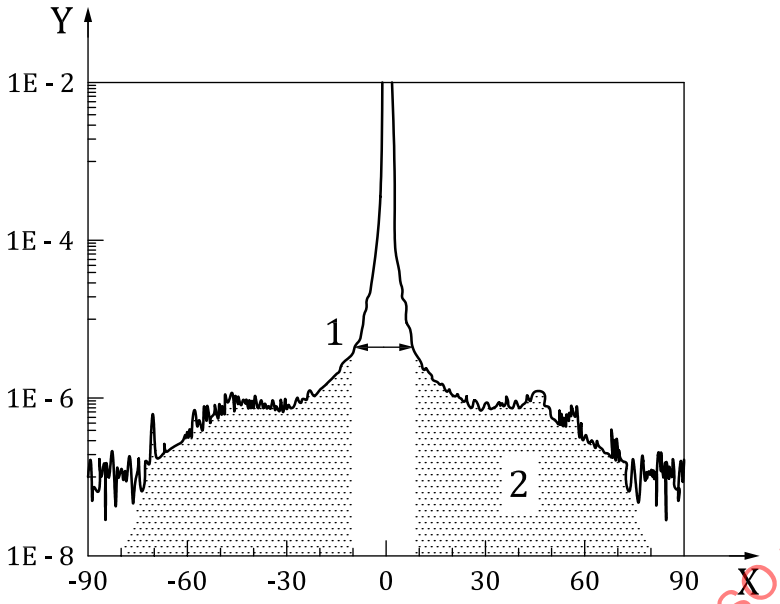


Key

X minimum scattering collection angle [degree]

Y collection ration [%]

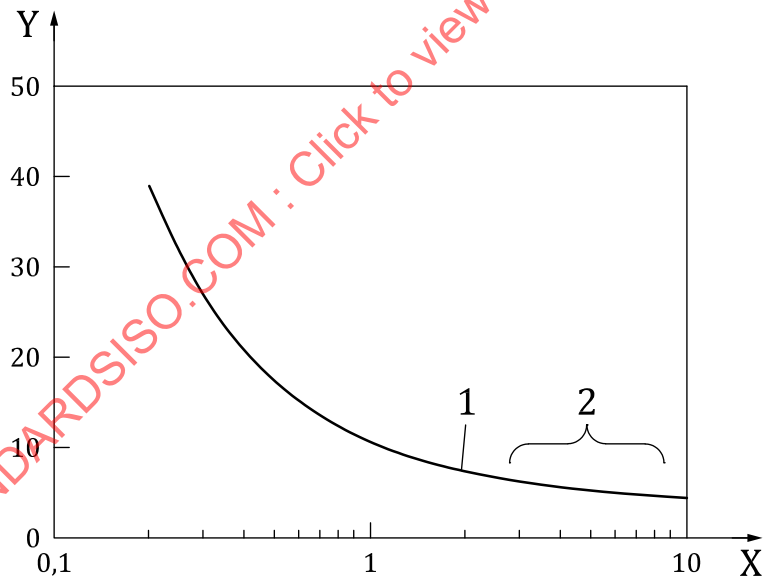
Figure C.2 — A collection ratio behaviour calculated with the ARS data in Figure C.1



Key

X	scattering angle [degree]	1	variation of minimum scattering collection angle for integration
Y	ARS [1/sr]	2	backward scattering

Figure C.3 — The ARS data of a highly reflective dielectric multilayer coating at 1064 nm



Key

X	integration from scattering angle [degree]	1	2° (ISO 13696)
Y	backward scattering [ppm]	2	2,7° to 8,6° (ISO 19962)

Figure C.4 — The backward scattering calculated by integrating the ARS of Figure C.3